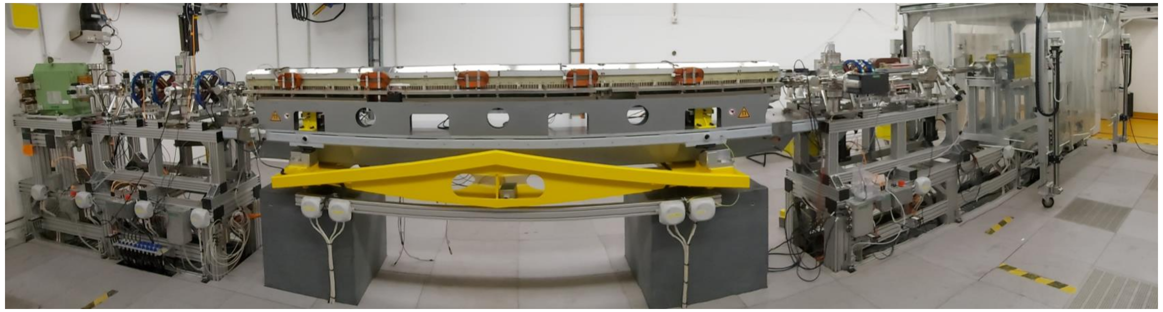
THz SASE and seeded FEL at PITZ: Introduction and Main Results

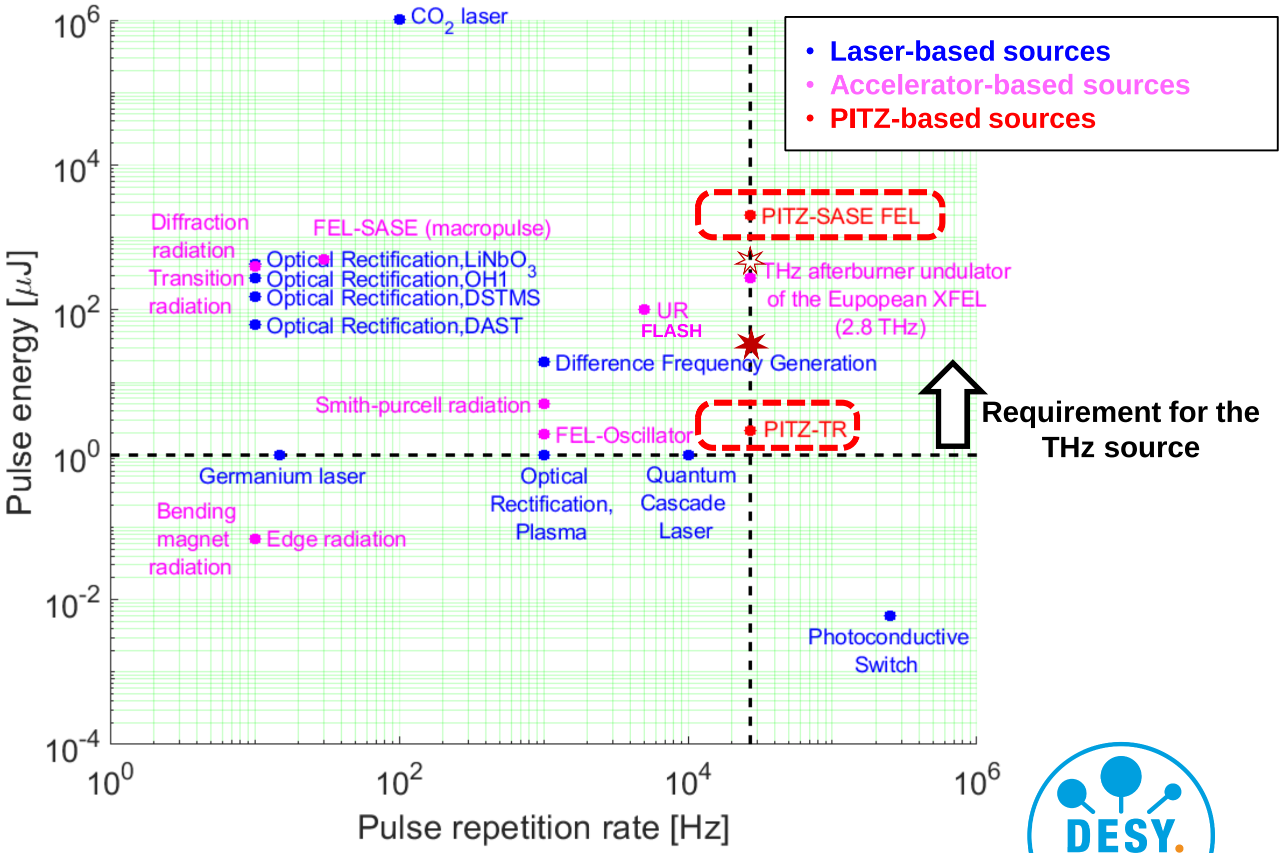
Photo Injector Test facility at DESY in Zeuthen: Development of high-power tunable accelerator-based THz source for the European XFEL

➔Proof-of-Principle experiment

Mikhail Krasilnikov for the THz@PITZ Team

Mini-workshop on THz@PITZ, 15.03.2023





HELMHOLTZ

DESY.

THz@PITZ Team and Collaboration

Strong team work!

DESY Zeuthen

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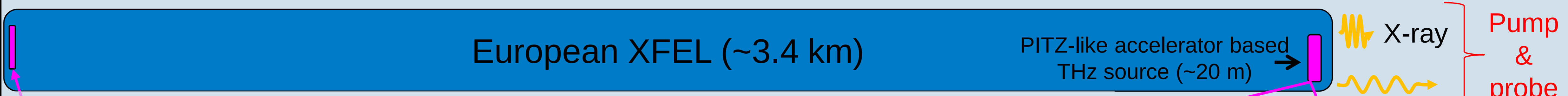
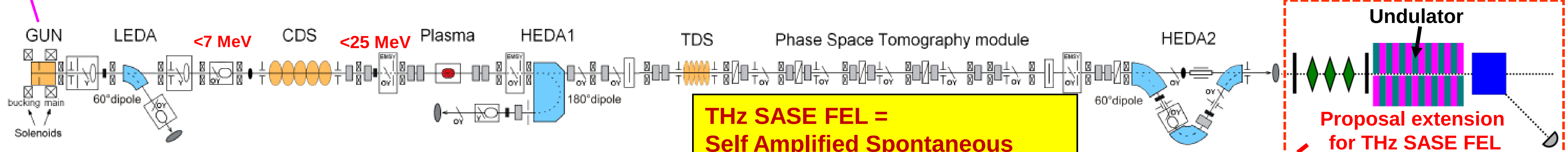
THz SASE FEL source for pump-probe experiments at European XFEL

PITZ-like accelerator can enable high-power, tunable, synchronized THz radiation



E.A. Schneidmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen),
"Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012

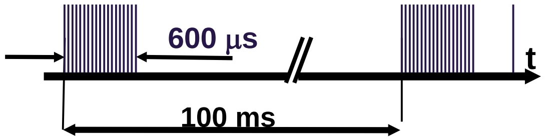


THz SASE FEL =
Self Amplified Spontaneous Emission Free Electron Laser

for λ_{rad} > 100 µm (f < 3 THz) → CTR / CDR / SUR?

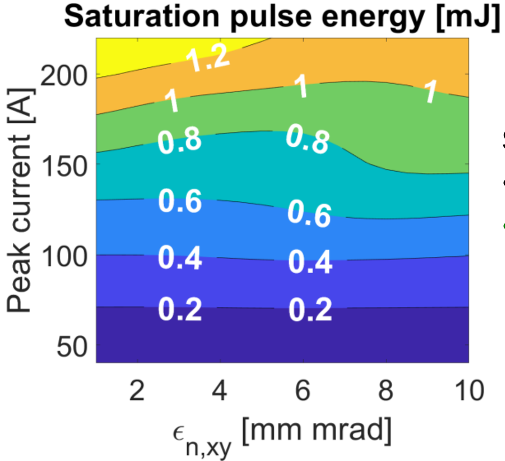
~mJ (sim) SASE FEL for λ_{rad} ≤ 100 µm (f ≥ 3 THz)

PITZ Highlights:



- Pulse **train** structure
- High **charge** feasibility (up to 6 nC), high QE photocathodes
- Advanced photocathode laser pulse **shaping**

Undulator for proof-of-principle experiment?



SASE FEL simulations assuming:

- Helical undulator with λ_u=40 mm
- 4 nC electron beam with 15 MeV/c and ~2 mm rms bunch length

Proof-of-principle experiment on THz SASE FEL at PITZ

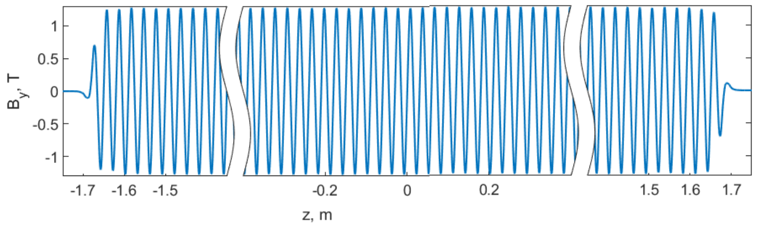
Using LCLS-I undulators (available on loan from SLAC)

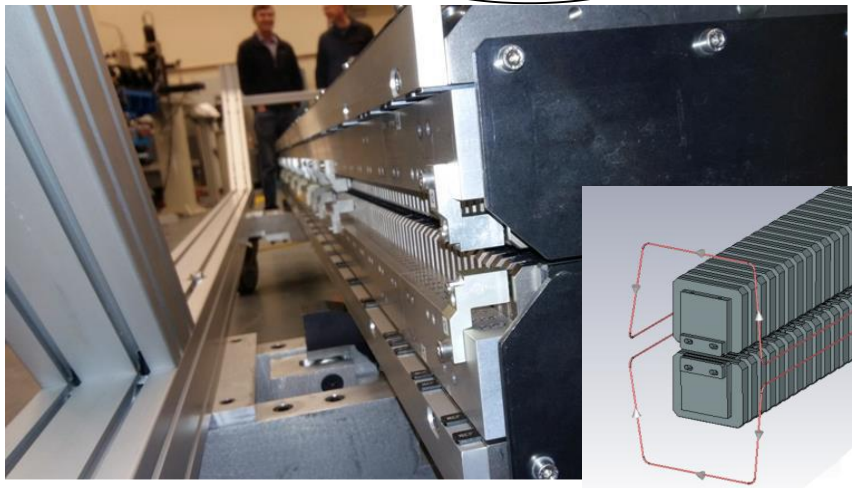
PITZ+ LCLS-I Undulator

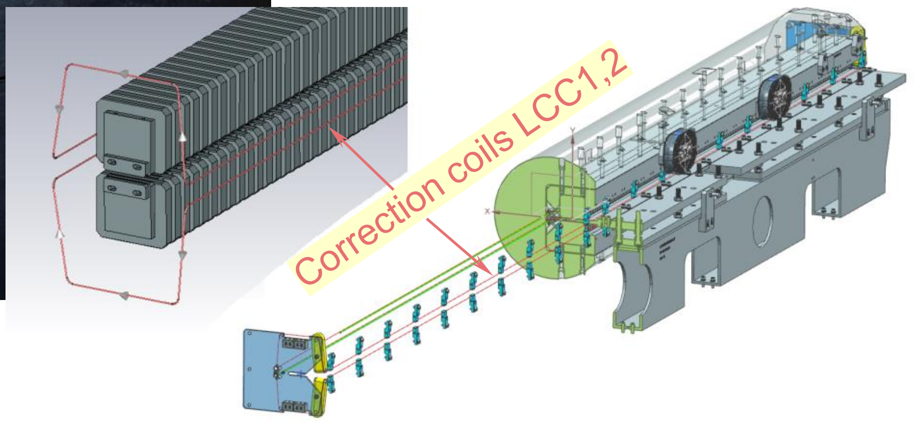
Proposal **“Conceptual design of a THz source for pump-probe experiments at the European XFEL based on a PITZ-like photo injector”** has been supported by the **E-XFEL Management Board** → dedicated R&D activities at PITZ → **Proof-of-principle experiments (2019-2023)**

Some Properties of the LCLS-I undulator

Properties	Details
Type	**planar hybrid** (NdFeB)
K-value	3.585 (3.49)
Support diameter / length	30 cm / 3.4 m
Vacuum chamber size	**11 mm x 5 mm** W
Period length	30 mm
Periods / a module	113 periods





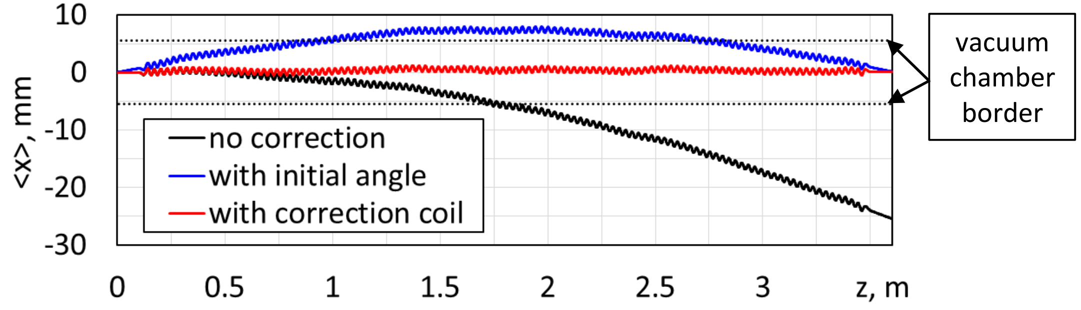


λ_{rad}~100μm → ~**17MeV/c**

Main challenges:

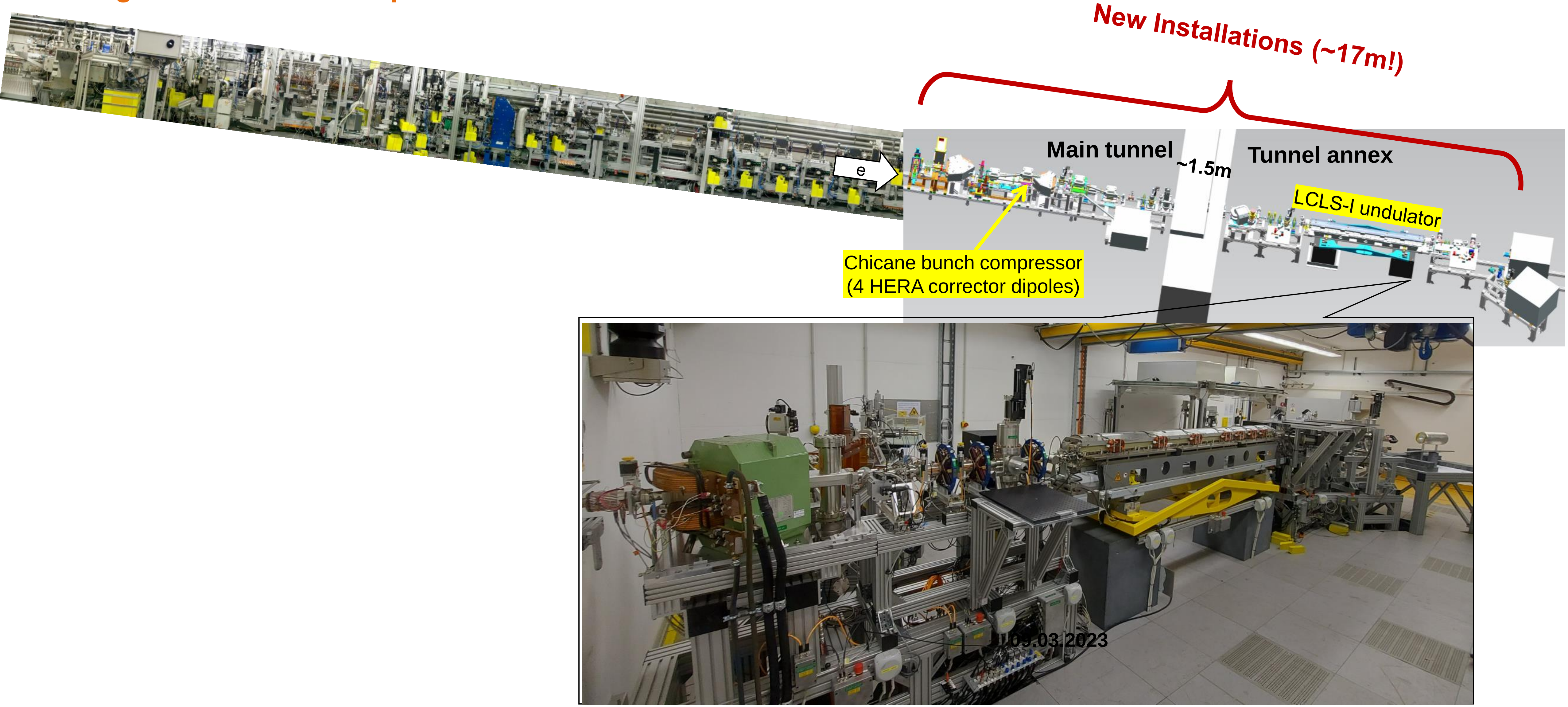
- Space charge effect
- Strong undulator (vertical) focusing + horizontal gradient
- “Full physics” might have to be considered
- Waveguide effect W
- Wakefields: geometric and conductive wall effects

Reference particle trajectories in the undulator with horizontal gradient



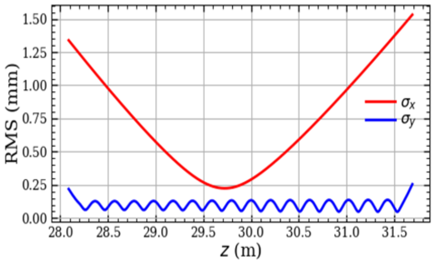
PITZ upgrade for the proof-of-principle experiment on THz source

Design and technical Implementation



THz SASE FEL at PITZ

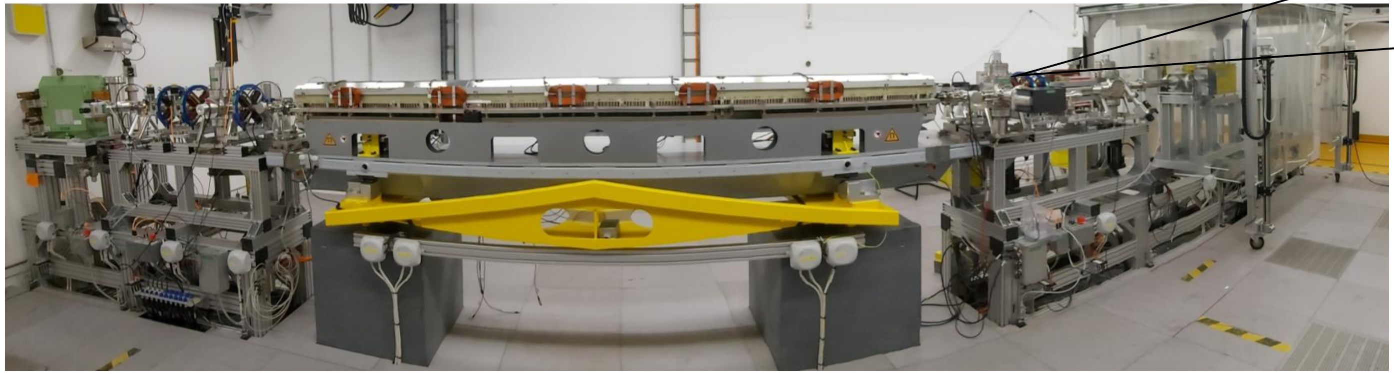
First Lasing on 09.08.2022



NB: SASE=start from noise

Pyroelectric detector

Beam matching and THz optimization:
→ talk of Xiangkun Li



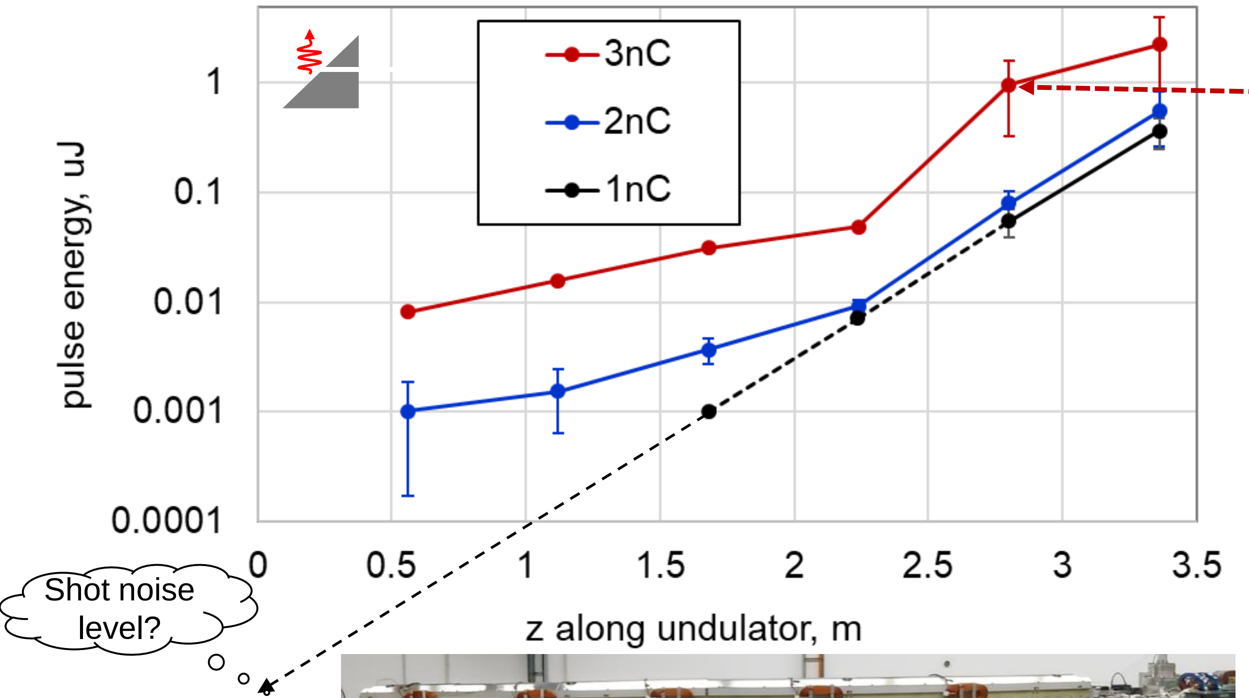
Details of THz diagnostics at PITZ:
→ talk of Prach Boonpornprasert

THz SASE FEL at PITZ: Gain Curves

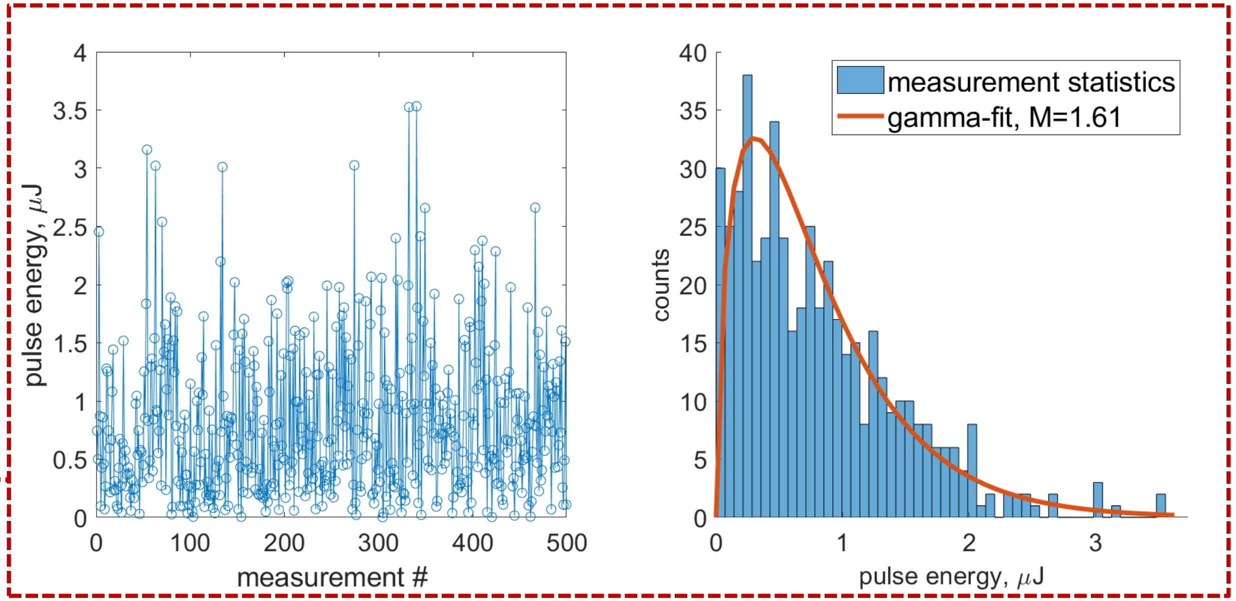
First Lasing Characterization

- Gain curves at 1nC, 2nC and 3nC for HIGH3.Scr2:
  - in-vacuum mirror with hole
  - No band-pass filter (BPF)
- **Lasing at ~100µm ➔ high gain THz SASE FEL at PITZ!**

Gain curves



Estimate?:
→ talk of Xiangkun Li



Probability distribution of the radiation pulse energy from SASE FEL operating in the high gain linear regime follows gamma distribution*:

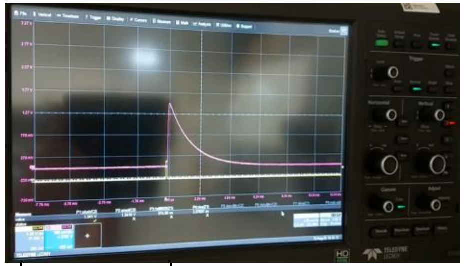
$$\rho(W) \propto \frac{M^M}{\Gamma(M)} \left(\frac{W}{\langle W\rangle}\right)^{M-1} \frac{1}{\langle W\rangle} \exp\left[-M\frac{W}{\langle W\rangle}\right],$$

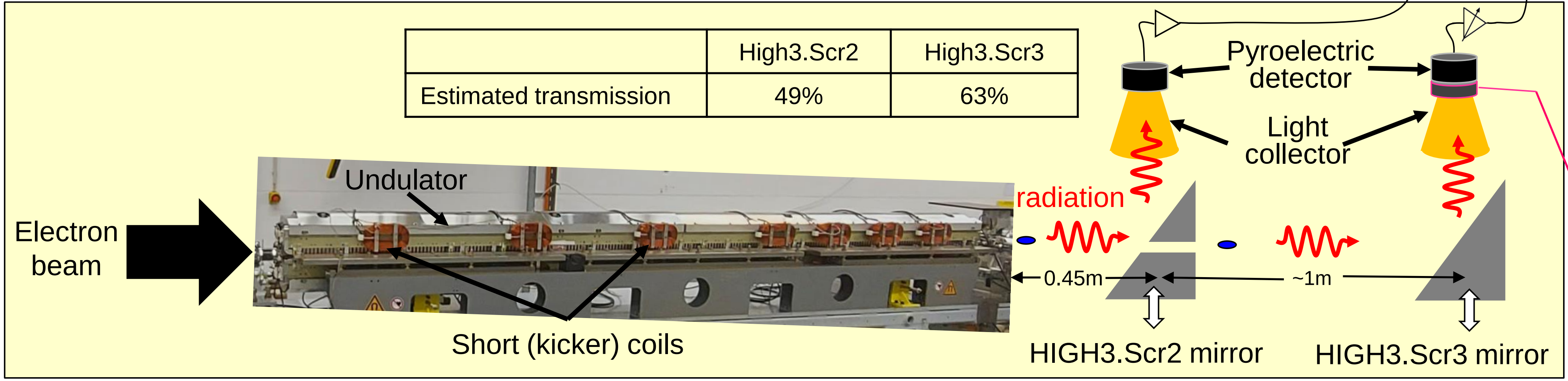
where $M = \frac{\langle W\rangle^2}{\sigma_W^2}$ is number of modes in the radiation pulse.

**E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, "Statistical properties of radiation from VUV and X-ray free electron laser", Opt. Commun., vol. 148, p. 383, March 1998. doi:10.1016/S0030-4018(97)00670-6*

THz SASE FEL at PITZ: THz diagnostics setup

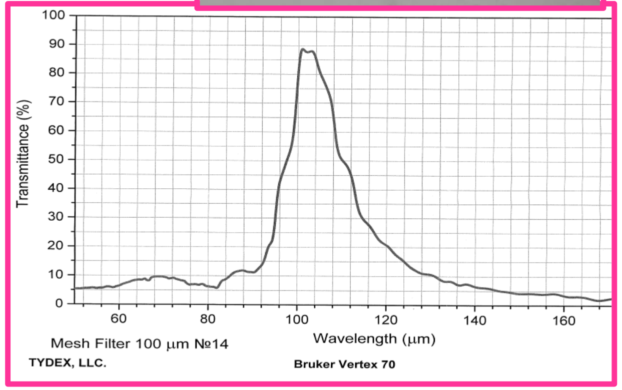
Startup: pyroelectric detectors with collector cones





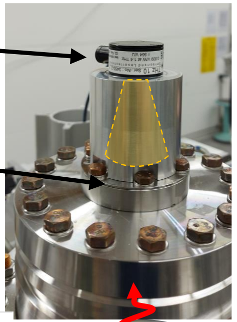
	High3.Scr2	High3.Scr3
Estimated transmission	49%	63%

Band-pass filter
BPF3.0-24
λ_0~102μm; δλ~12μm
<f>~3THz

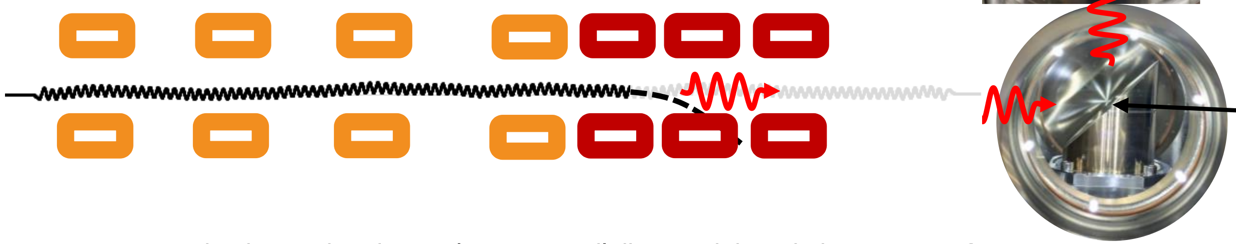


Pyroelectric detector THz10

Diamond 20mm viewport



Simplified layout of the gain curve measurement setup

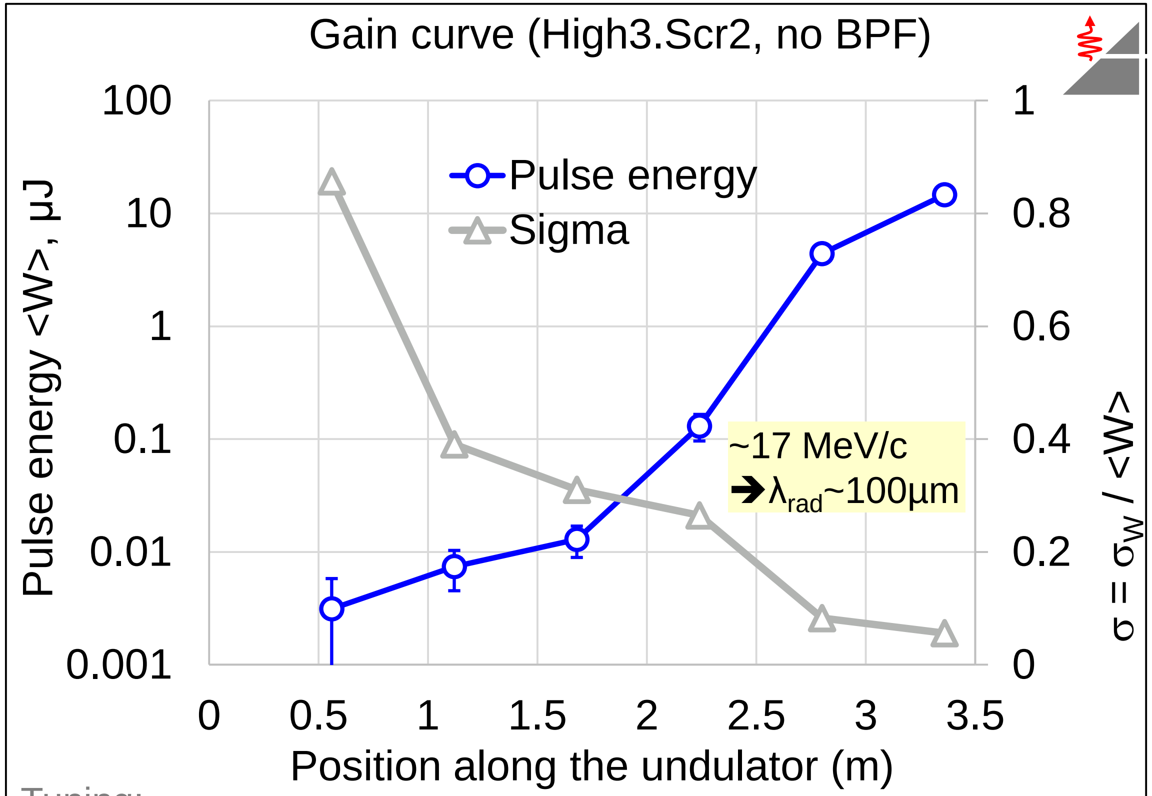


In-vacuum mirror

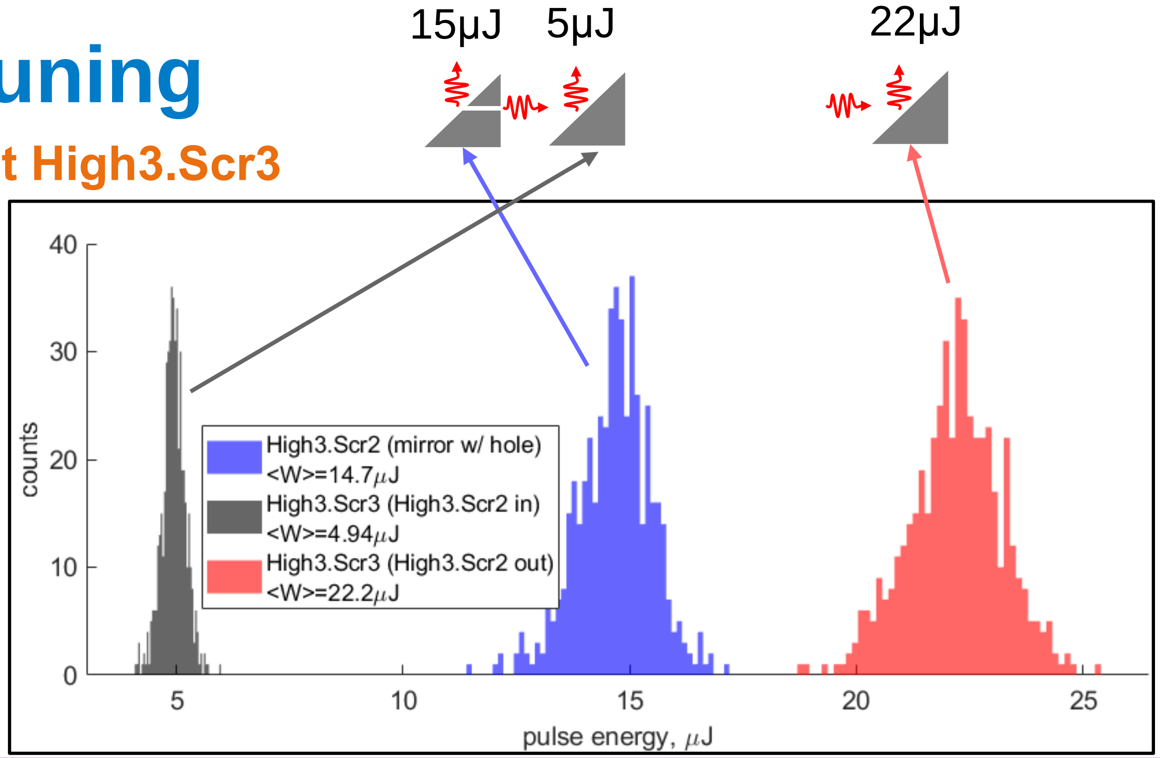
Details of THz diagnostics at PITZ:
→ talk of Prach Boonpornprasert

THz SASE FEL at PITZ: Further Tuning

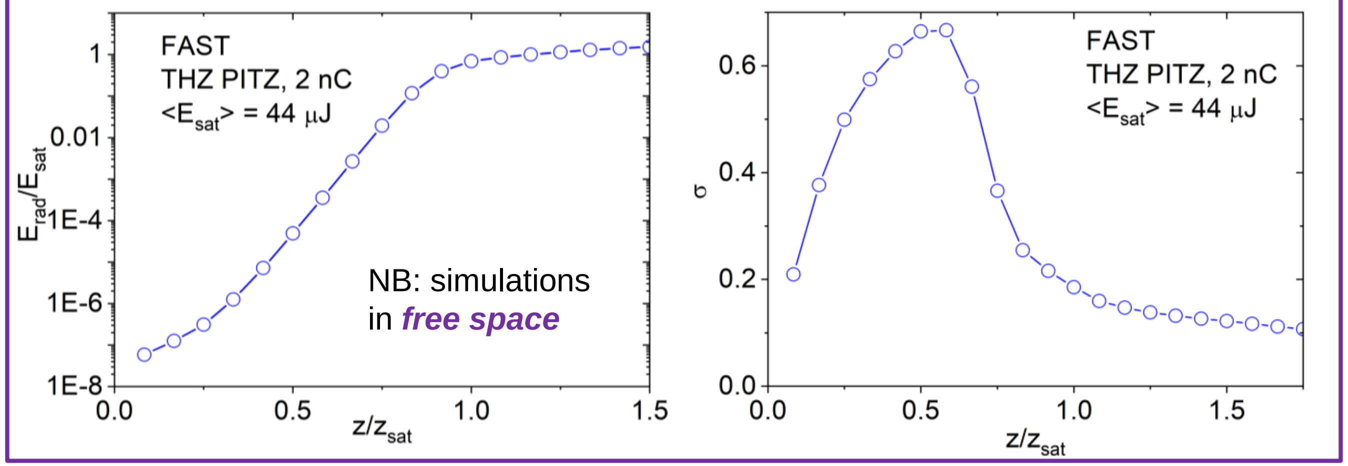
Saturation observed for 2nC: max pulse energy~22μJ at High3.Scr3



Tuning: started from 3nC!



FAST Simulations (M. Yurkov)

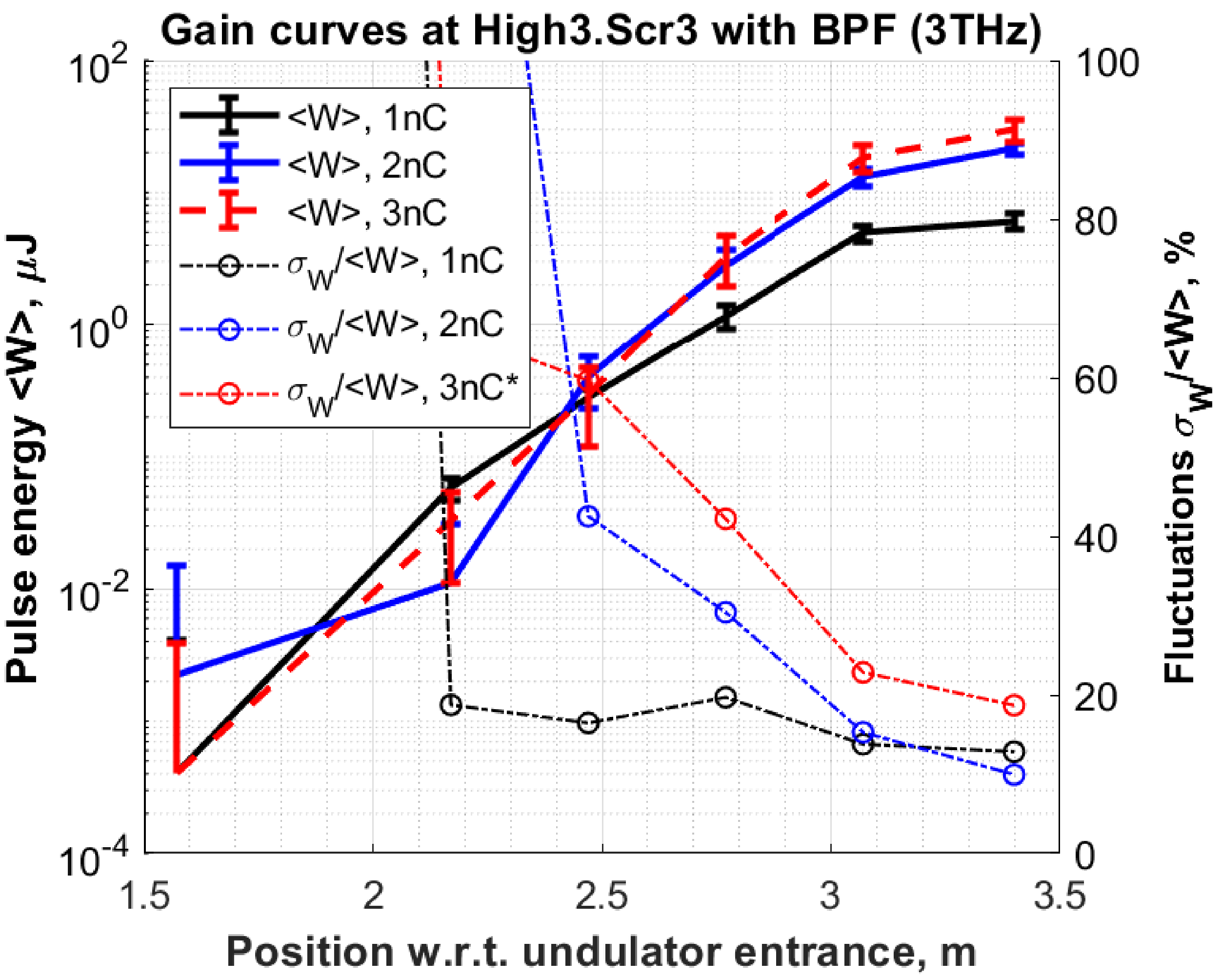


NB:
- Strong ***waveguide regime*** of SASE FEL W
- WARP (PIC) simulations with vacuum chamber border yield ×2-3 higher THz pulse energy

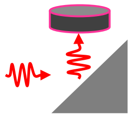
More simulations:
→ talk of Xiangkun Li

SASE Gain Curves at High3.Scr3 with BPF

In-vacuum mirror without hole + 3THz Band-pass filter



Optimization progress
<pulse energy> (fluctuations)
High3.Scr2 vs High3.Scr3



Bunch charge	1st lasing, no BPF	Tuning, BPF
1nC	0.36 uJ (32%)	6.12uJ (13%)
2nC	0.55uJ (52%)	21.44uJ (10%)
3nC*	2.26uJ (78%)	29.67uJ (19%)

* Not fully optimized

NB:
- Calculations for the BPF (λ_0~102μm) → <Pz>~16.5MeV
- Experimentally → <Pz>~17MeV/c

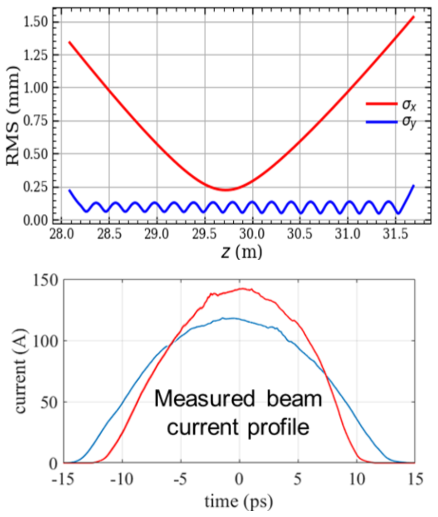
Reference: Saldin E.L., Schneidmiller E.A., Yurkov M.V. "The physics of free electron lasers" - Berlin et al.: Springer, 2000.

Reference case: 2nC

Cross-check with linear theory of FEL amplifier with diffraction effects

e-beam

parameter	value
Energy, E_0	~17MeV
γ	34
$<\sigma_x>$	0.75mm
$<\sigma_y>$	0.2mm
$<\sigma_r>$	0.55mm
charge	2nC
I_{peak}	125A
$\varepsilon_{n,x,y}$	5 mm mrad
σ_E	~10keV (slice)



FEL radiation

parameter	value
λ_{rad}	~90μm
Q	0.429
A_{JJ}	0.745
θ_l	0.10
γ_l	12.6
Γ	$(0.237\text{m})^{-1}$

$$\lambda_{rad} = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$Q = \frac{K^2}{4+2K^2}$$

$$A_{JJ} = J_o(Q) - J_1(Q)$$

$$\theta_l = K/\gamma$$

$$\frac{1}{\gamma_l^2} = \frac{1}{\gamma^2} + \frac{\theta_l^2}{2}$$

$$\Gamma = \sqrt{\frac{I_{peak}A_{JJ}^2\omega^2\theta_l^2}{2I_A c^2\gamma_l^2\gamma}}$$

FEL dimensionless

Parameter	Value
Diffraction B	~0.1
SC $\hat{\Lambda}_p^2$	0.9
FEL ρ	0.01
EnSpread $\hat{\Lambda}_T^2$	0.003
Waveguide $\Omega*$	5.3

$$B = \frac{2\Gamma\sigma_r^2\omega}{c}$$

$$\hat{\Lambda}_p^2 = \frac{4c^2}{[\theta_l\sigma_r\omega A_{JJ}]^2}$$

$$\rho = \frac{\gamma_l^2\Gamma}{\omega/c}$$

$$\hat{\Lambda}_T^2 = \frac{\sigma_E^2}{[E_o\rho]^2}$$

$$\Omega = \Gamma R_{eff}^2\omega/c$$

undulator system

parameter	value
λ_u	30mm
K	3.34 (3.47)
Vacuum chamber R_{eff}	4.2mm

$$E_x(z) \propto \exp(\Lambda\cdot z)$$

Reference case: 2nC

Cross-check with linear theory of FEL amplifier with diffraction effects

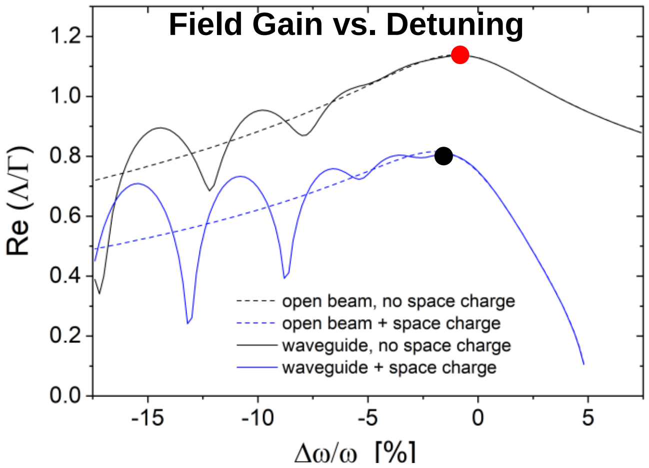
The gain parameter of the FEL amplifier

$$\Gamma = \sqrt{\frac{I_{peak} A_{JJ}^2 \omega^2 \theta_l^2}{2 I_A c^2 \gamma_l^2 \gamma}} = (0.237m)^{-1}$$

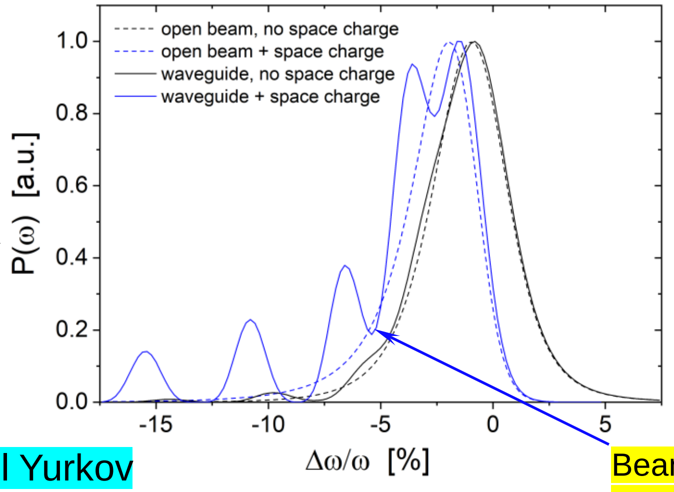
Parameter	Value
Diffraction B	~0.1
SC $\hat{\Lambda}_p^2$	0.9
FEL ρ	0.01
EnSpread $\hat{\Lambda}_T^2$	0.003
Waveguide $\Omega*$	5.3

Eigenvalue problem → beam radiation modes

$E_x(z) \propto \exp(\Lambda \cdot z)$, Λ → field gain (ReΛ)



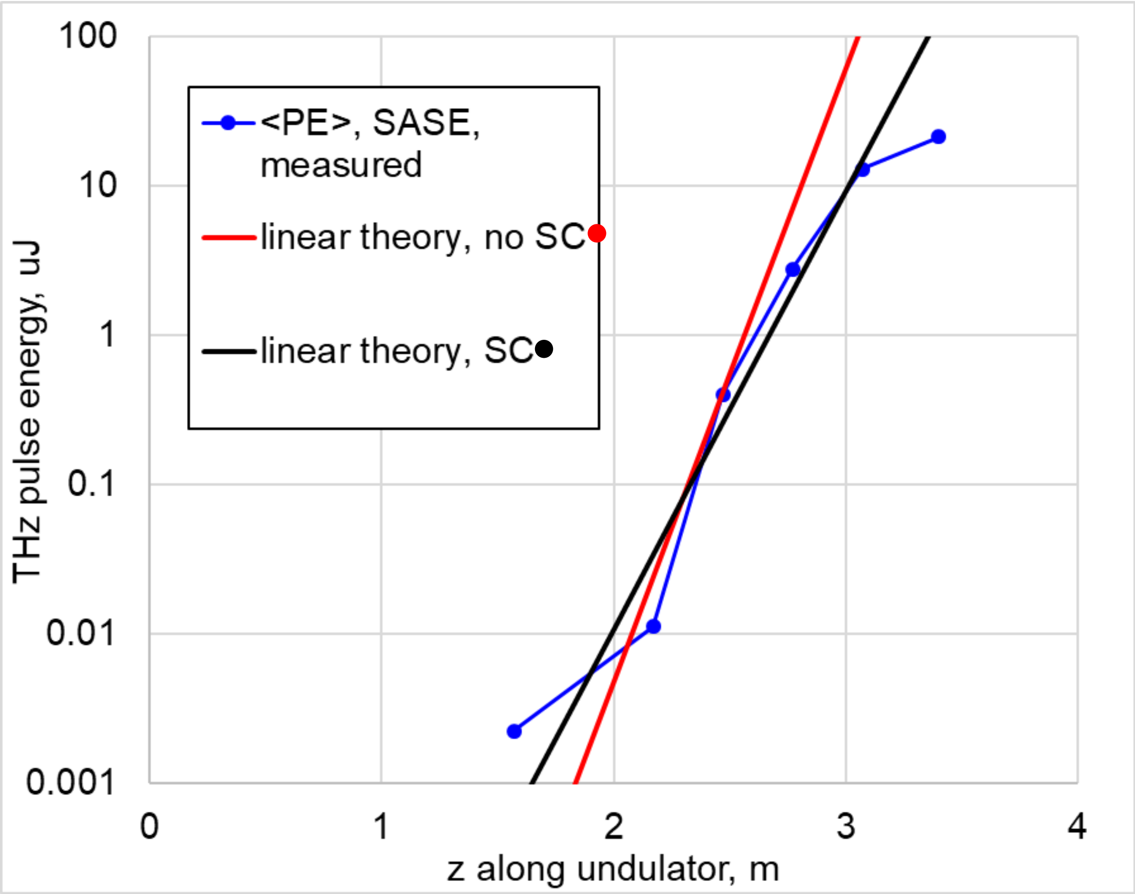
Expected power spectrum (the high gain regime at the onset of saturation)



Calculations:
courtesy Mikhail Yurkov

Beam radiation modes in waveguide: should be measurable?

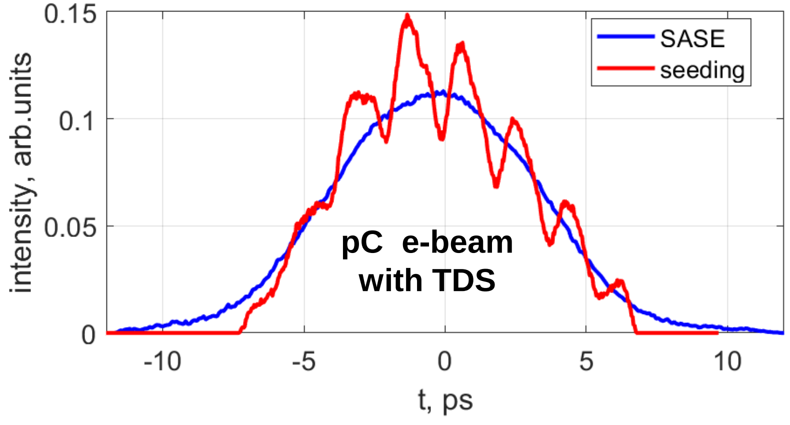
SASE 2nC: Linear theory versus measurements



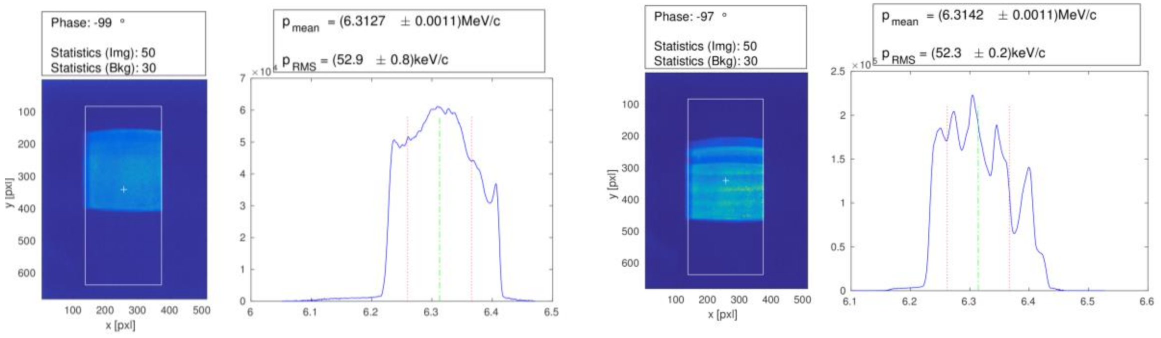
First Seeding Experiments

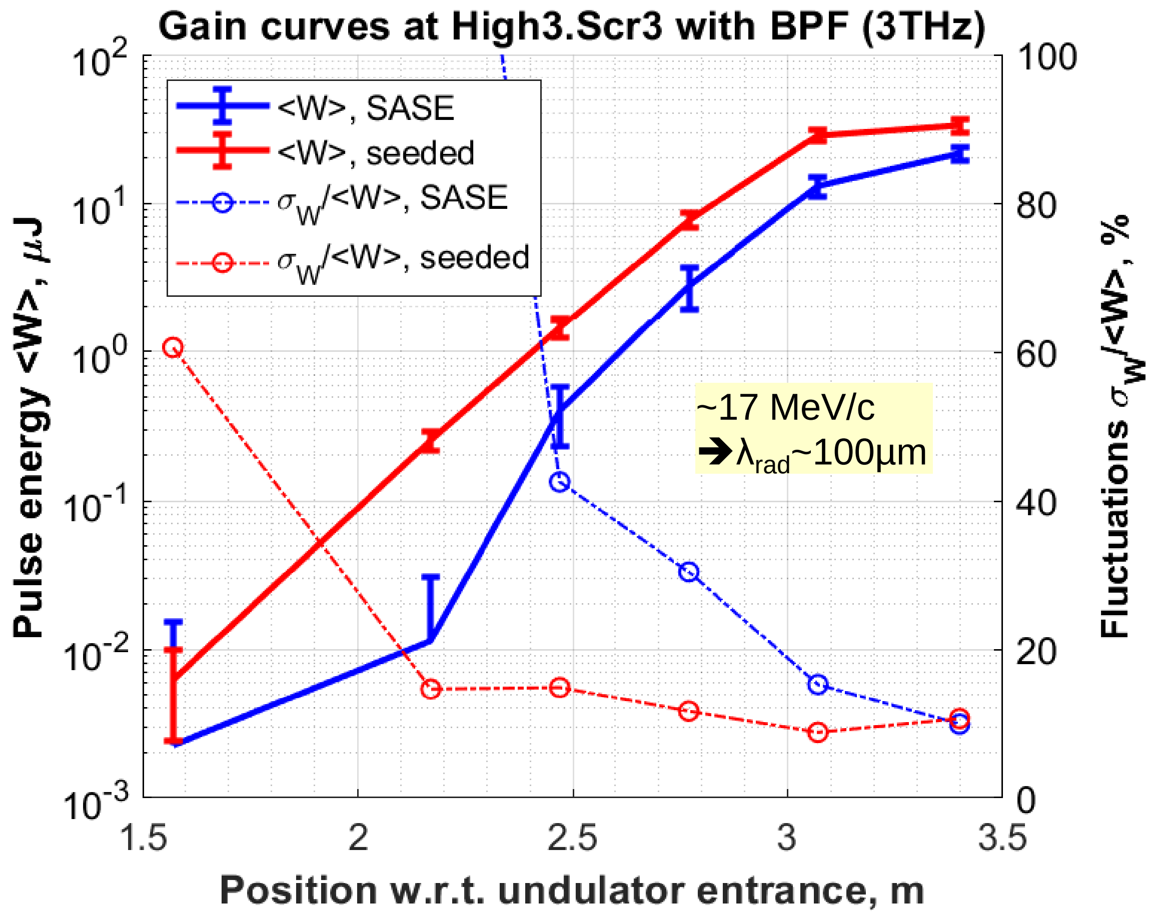
SASE vs. seeded THz FEL with modulated photocathode pulse (preliminary results)

- Gain Curves at HIGH3.Scr3 (THz mirror w/o hole) with BPF
- THz FEL Seeding experiments
  (**2nC** e-beam with modulated photocathode laser pulse):
  <W>→ **33µJ** vs **21µJ** from SASE



P_z-distributions of e-beam (2nC) after gun (LEDA)



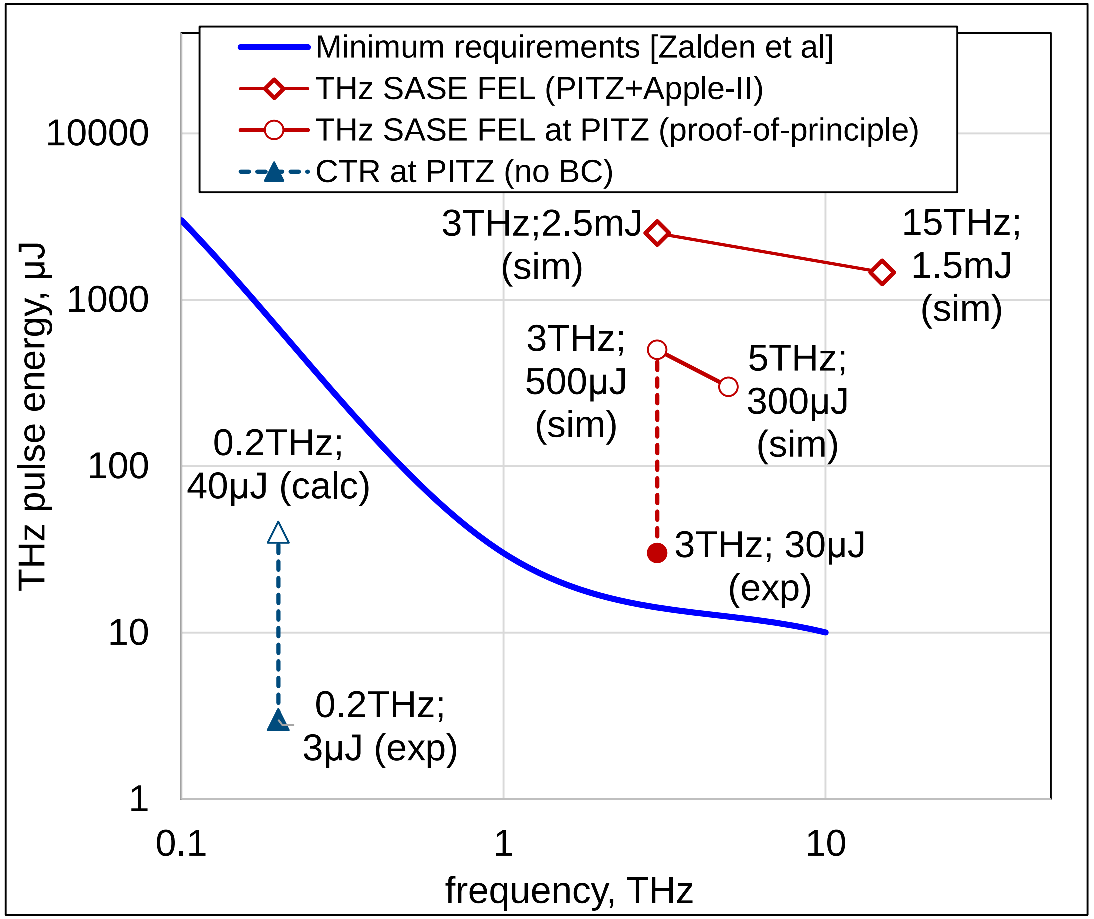


More details (simulations):
→ talk of Georgi Georgiev

Seeded THz FEL gain curve:
- Higher energies + earlier start
- Better stability

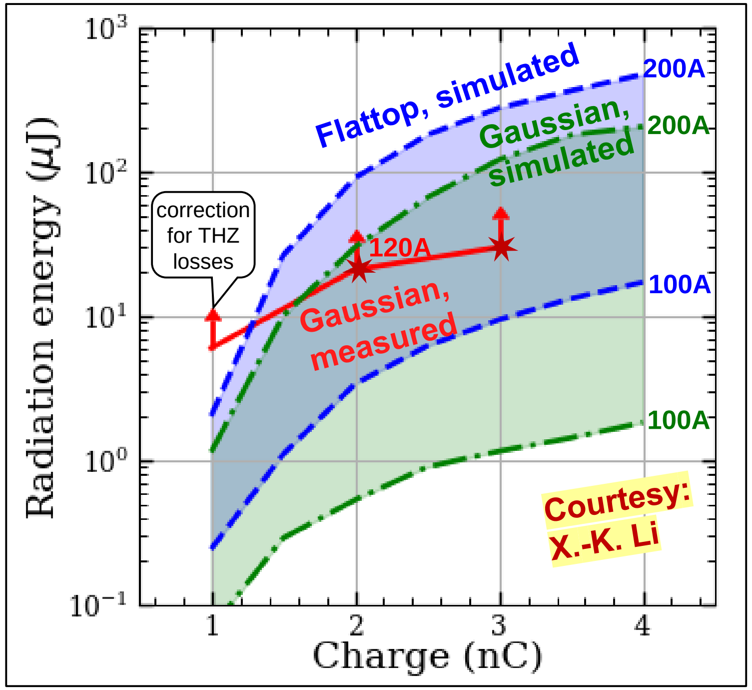
Proof-of-principle Experiment on THz Source at PITZ

Where we are now and the way to go



parameter	Min. requirements [1]	PITZ (exp)
Bandwidth	1…0.05	~0.02
f [THz]	0.1…**3…20**…30	**3…5**
Pulse energy	3mJ@0.1THz; 30µJ@1THz; 10µJ@10THz	**30µJ@3THz**
CEP	yes	no*
Rep.Rate (burst)	0.1MHz…4.5MHz	1MHz*
Synchronization	<0.1/f	challenge
Polarization	optional	yes

Gaussian photocathode laser, **2-3 nC** bunch charge



Scientific requirements:

[1] P. Zalden, et al., "Terahertz Science at European XFEL", XFEL.EU TN-2018-001-01.0

"..3 to 20 THz is the most difficult to cover by existing sources; at the same time, many vibrational resonances and relaxations in condensed matter occur at these frequencies."

Conclusions

THz SASE FEL at PITZ

- Proof-of-principle experiment ongoing @PITZ (supported by EXFEL):

  → LCLS-I undulator (challenging parameters for THz, but it works)

  → **1st THz SASE FEL Lasing → 09.08.2022**

  → High gain measured !

  → Strong dependence on beam current and transport /matching

  → Saturation at **>20µJ** with 2nC

  → First seeding experiments **>30µJ** with 2nC modulated beams

High-gain THz SASE FEL at a PITZ-like accelerator → **it works!!!**

→ **bunch charge within long bunch length (>>λ_{rad}) = source of high THz pulse energy!**

→ **+seeding options for stabilization**

Machine Advisory Committee (MAC) 27th Meeting

First Lasing of a THz SASE FEL at PITZ

Findings:

The first lasing of the THz FEL developed at PITZ was presented. The device consists in the implementation of the injector developed for the XFEL (Gun5) to drive a THz single pass FEL amplifier. This FEL has an distinguishing feature with respect to other THz sources based on transition radiation or optical rectification that is the capability of producing longer, spectrally narrower THz pulses.

The FEL amplification up to saturation was demonstrated, FEL pulse energies at the level of tens of microjoules were measured. The role played by the bunch charge and peak current was investigated. The interplay between beam manipulation at the gun by a modulation of the cathode laser and space charge effects along the transport to the undulator was used to generate a pre-bunching in the electron beam density at the undulator entrance, to seed the amplifier. A consistent increase of the FEL pulse energy and a stabilization of the pulse energy fluctuations are observed in this “seeded mode of operation”.

Comments:

The MAC is **impressed by this scientific development carried out at PITZ**, the project **met the expectations** and went even **beyond**, building up a scientific programme centered on a THz FEL implementing new concepts such as the idea of pre-modulation of the beam, that may have an impact on the design of similar devices in the future.

The PITZ FEL is driven by a beam with the **same temporal structure** of the XFEL. The realized device represents the proof of concept of a system that could be considered in combination with the XFEL beam for THz-pump X-ray probe experiments. Accommodated in a suitable environment close to an experimental station of one of the XFEL branches, such a device could deliver a beam synchronized to the XFEL to be coupled to the X-ray beam. The **seeding** implemented by modulating the photoinjector laser at the cathode can also have an effect on the **control of the phase** of the THz light, which can be pretty important for eventual THz-pump X-ray probe experiments.

Recommendations:

Based on the very encouraging THz results the MAC **recommends extending the project beyond the 2023 deadline**. The preparation of a **conceptual design report** of a source optimized for pump and probe experiments in combination with the XFEL should be prepared based on the experience done with this FEL at PITZ. A plan on how to integrate it with an experimental hutch at the Eu-XFEL as a tunable and synchronized probe pulse should be studied.

CDR and next steps

Machine Advisory Committee (MAC) 27th Meeting

Answer to the MAC charges 3 and 4 (First Lasing of a THz SASE FEL at PITZ)

3. What are the most important measurements to verify the concept by the end of 2023?

- Further characterization of the **“seeding” concept**: a phase stable coherent source can be pretty important for eventual THz-pump X-ray probe experiments. The characterization of the field with an EOS setup or other methods to measure the phase locking of the THz light with an external ultrafast laser pulse would be important information. Further investigation on beam transport for the space charge dominated beam may be necessary.

- The installation of a magnetic compressor is foreseen before the project completion. The compressor in combination to the photocathode laser seeding to tune the seed to the THz resonance should be explored.

- Investigations (simulation/calculation) on the optimal bunch charge for a realistic undulator chamber (4nC in a small chamber produces a lot of wake fields, which can be reduced by a larger tube). Even if a CDR aims at an ideal machine, the undulator gap and the corresponding period length should be chosen as realistically as possible.

4. How could/should the theoretical and experimental research continue after 2023? Possible topics could be:

a) Expand / improve THz diagnostics (e.g., try EOS, other advanced THz diagnostics not included in the original project)
The measurement of the radiation spectrum with an EOS or with a Michelson interferometer would provide important information about the behavior of the source
The measurement of the radiation spectrum with an EOS or with a Michelson interferometer would provide important information about the behavior of the source

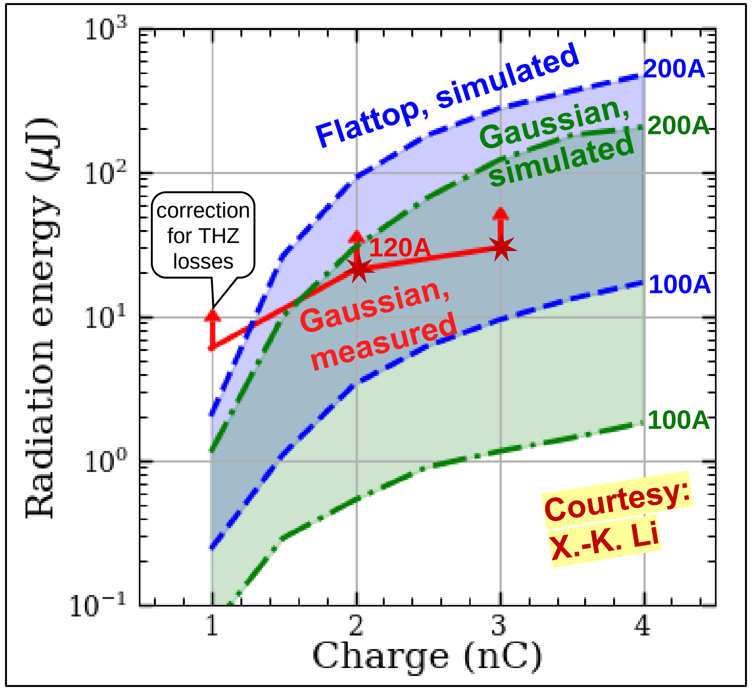
b) Further exploration of the parameter space (bunch compressor for SASE, seeding setups as well as for Superradiant regime, various seeding methods, bunch profile shaping, etc.)
The installation of a magnetic compressor is foreseen before the project completion. The use of the compressor in combination to the photocathode laser seeding to tune the seed to the THz resonance should be explored.

c) Can we envision user experiments (THz only) to test the THz radiation properties using the proof-of-principle experimental setup?
Concerning the use of this source as a user devoted facility could be premature, **but pilot experiments could be carried out**, such as a study of the induced transparency and/or harmonic generation in graphene (see e.g. *Mics, Z., Tielrooij, KJ., Parvez, K. et al. Thermodynamic picture of ultrafast charge transport in graphene. Nat Commun 6, 7655 (2015) https://doi.org/10.1038/ncomms8655*).

THz@PITZ: next steps

2023

- The current project (Proof-of-principle) → till end 2023:
  - Additional 4 weeks of operation (Σ=11)
  - Currently – the only Gaussian PC laser pulses
  - Milestone: **100μJ**
  - NEPAL-P (~mid. 2023) → Flattop PC laser pulses (+modulation?)
  - Milestone: **200μJ+?**
  - **5THz** (tunability demonstration)
  - Seeding studies (also with BC)
  - SUR and CTR experiments with BC
  - Detailed characterization of THz



- "Conceptual design of a THz source for pump-probe experiments at the European XFEL based on a PITZ-like photo injector" -> CDR is expected as a delivery of the current project by the end of 2023:
  - Summarize experience from the proof-of-principle experiments on THz source at PITZ
  - Supply experimental data with theoretical modeling and numerical simulations
  - Conceptual design of the "ideal machine"

Status → talk of Prach Boonpornprasert

THz@PITZ: next steps

Possible topics for THz R&D 2024+?

- Proposal to EuXFEL-user R&D:
  - THz diagnostics: EOS, and other advanced tools (spectrometry?)
  - CTR/CDR (wavelength>100um) optimization
  - Pilot experiments with THz@PITZ
  - TDR on THz source for EuXFEL
  - “Ideal” THz undulator design
  - “Ideal” BC for THz machine

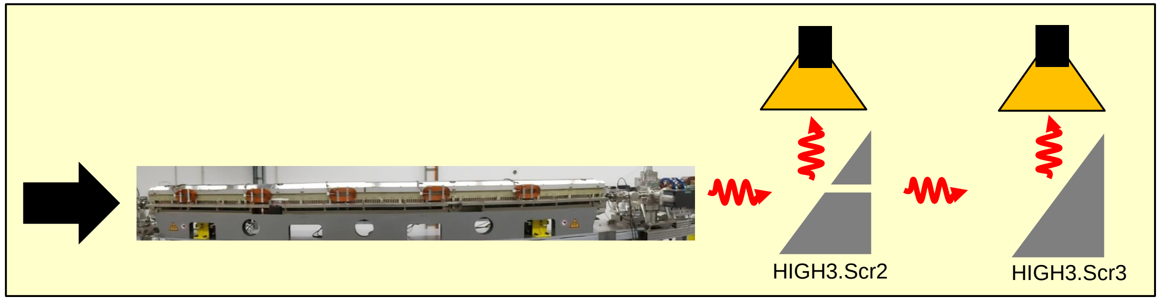
1. Not everything will be possible!
2. Priorities to be set (importance, resources and risks)!
3. Try to iterate/coordinate with EuXFEL (strategy 2030+?)
4. Any ideas/arguments are welcome!

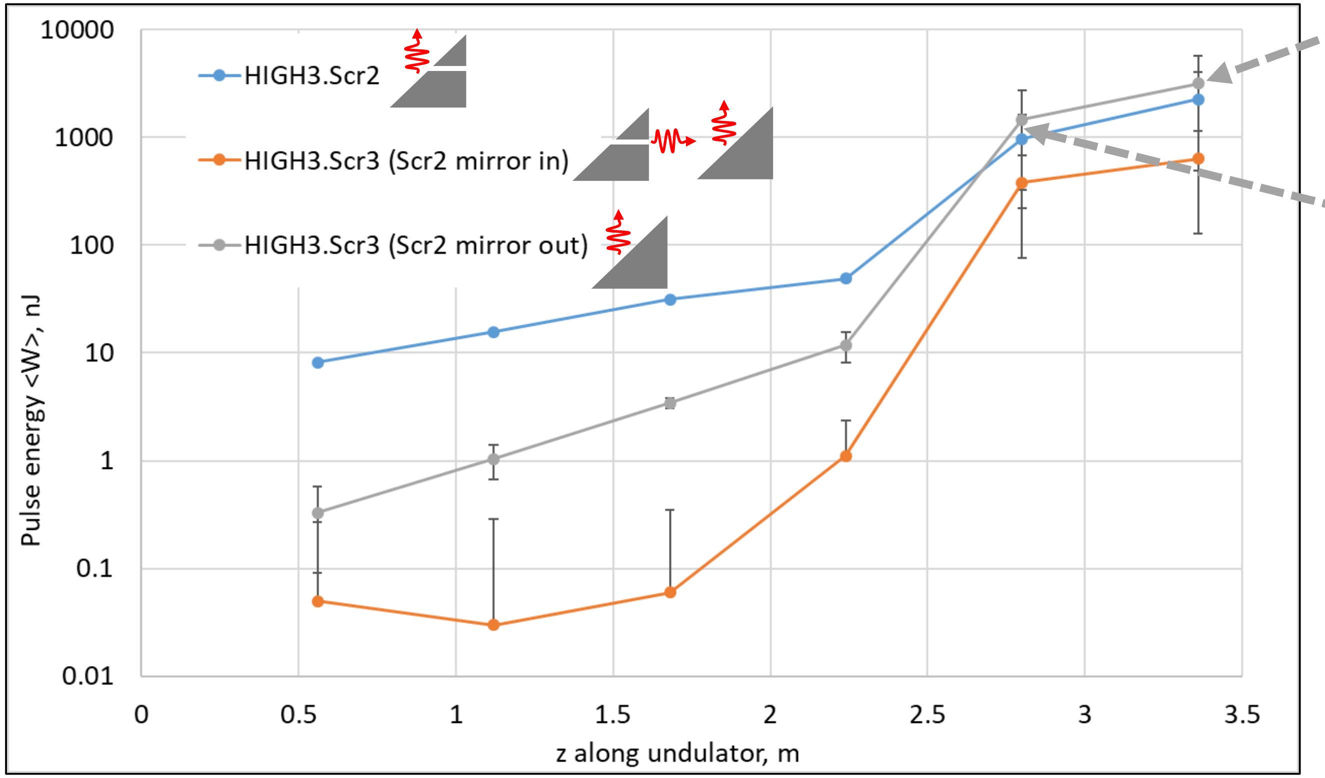
- Proposal to EuXFEL-accel. R&D:
  - Exploration of parameter space of the THz SASE and seeded FEL at PITZ
  - “Ideal” THz machine optimization
  - THz seeding:
    - PC laser pulse modulation with several methods
    - Two-beam scheme
    - Other methods: DLW, external source, etc.
  - ML developments for the accelerator-based THz source optimization / tuning

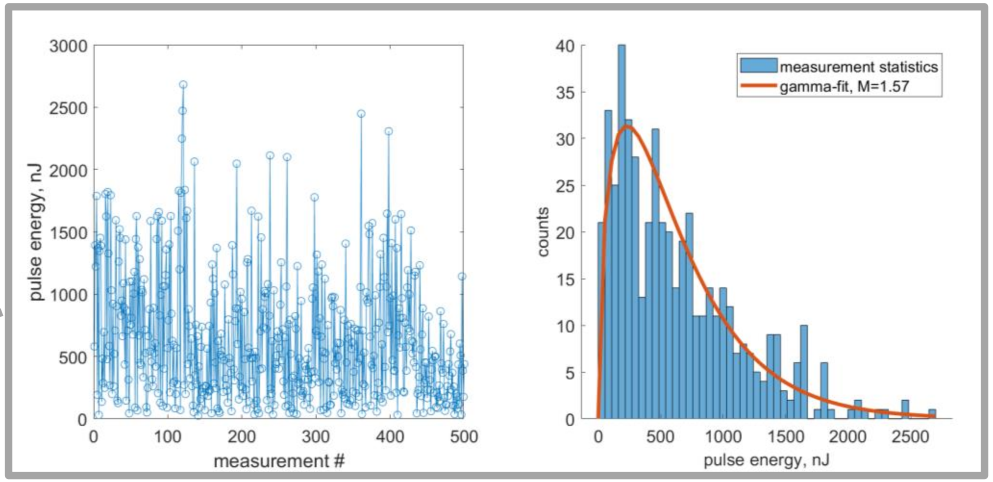
Backup slides

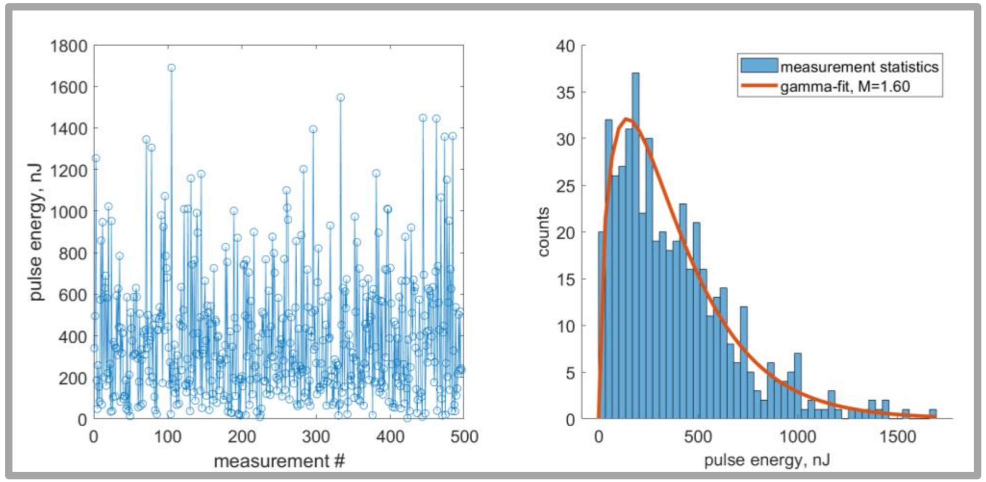
THz SASE FEL at PITZ: Gain Curves (3nC)

Measured pulse energy vs position along undulator for different locations

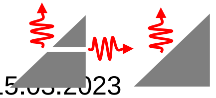




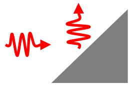




2.3µJ 0.6µJ



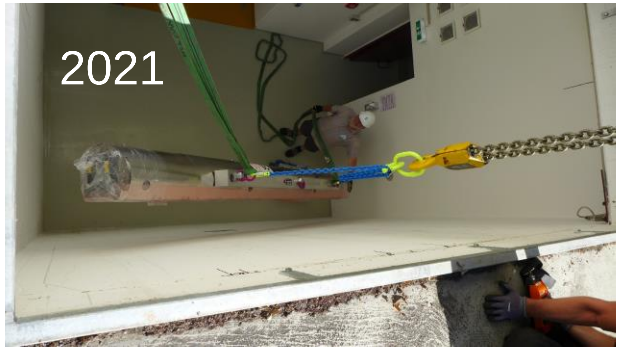
3.1µJ



THz SASE FEL at PITZ: Realization

The tunnel annex → new accelerator tunnel (Tunnel 2)

- Tunnel 2:
  - realization of a new interlock area, operation permission
  - improve radiation shielding
  - 16t movable access gate and protection wall
  - infrastructure in the tunnel annex:
    crane and drillings (cabling and tunnel connection)
- LCLS undulator:
  - Transport SLAC → DESY Hamburg
  - DESY Hamburg: Field quality check
  - Transport → DESY Zeuthen, installation in tunnel 2



- Design, production / procurement of new components (~100!):
  - Tunnel 1: BC and new beam dump
  - Both tunnels: installation of the new beamline components:
    - 6 x BPMs
    - 7 x Screen Stations
    - 6 x Dipoles
    - 8 x Quadrupoles
    - 6+ x Rotational steerers
    - 7 + 2 Correction coils at undulator
    - …
- Accelerator infrastructure
  (power supplies, network connections
  controls)

THz SASE FEL at PITZ: Realization

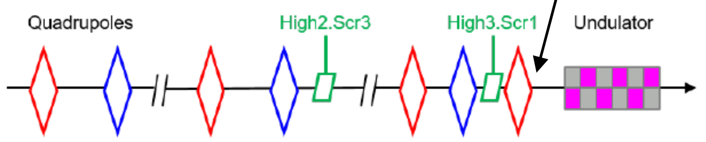
THz Beam line in Tunnel 2

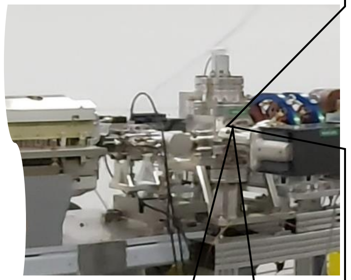
THz Beamline Commissioning

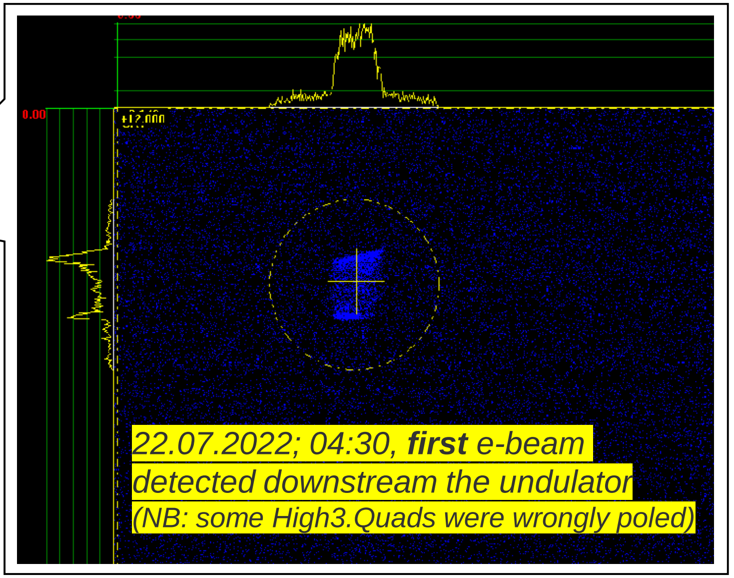
Main challenge – matching into the LCLS-I undulator (planar + strong field + strong vertical focusing + horizontal gradient +)

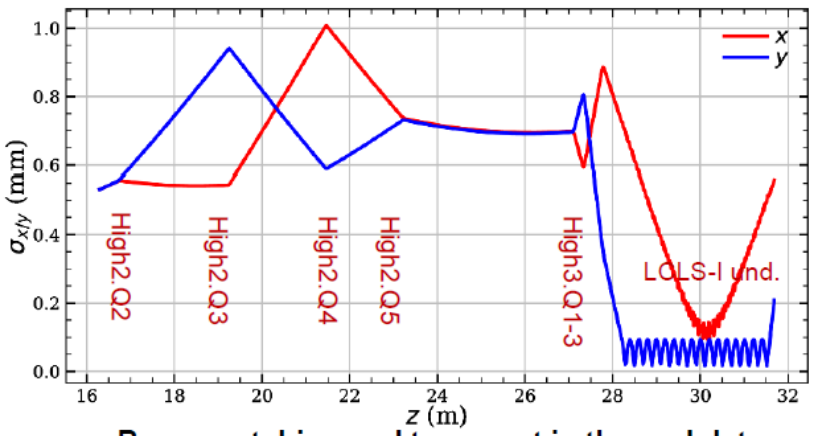
Procedure for beam matching into the LCLS-I undulator

No screen behind High3.Q3!

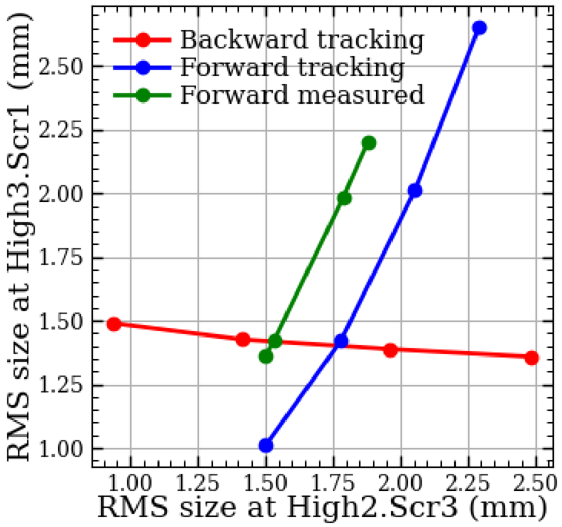


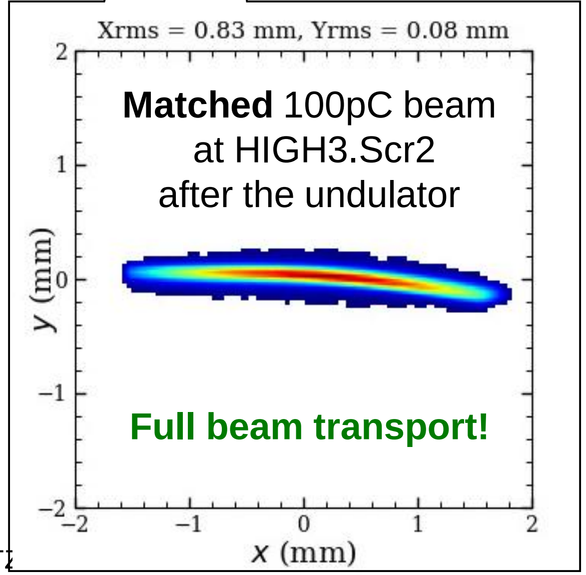






Beam matching and transport in the undulator



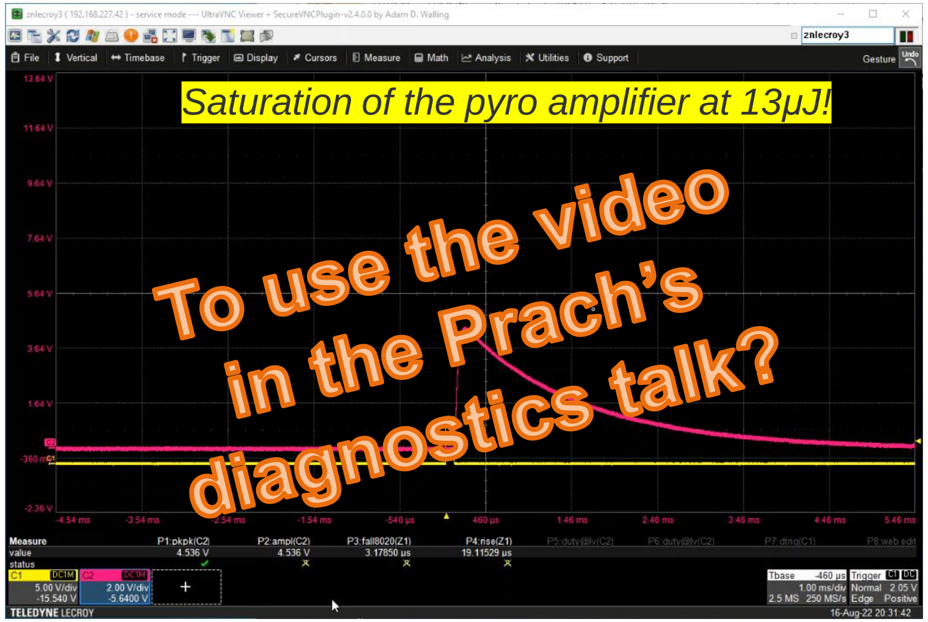


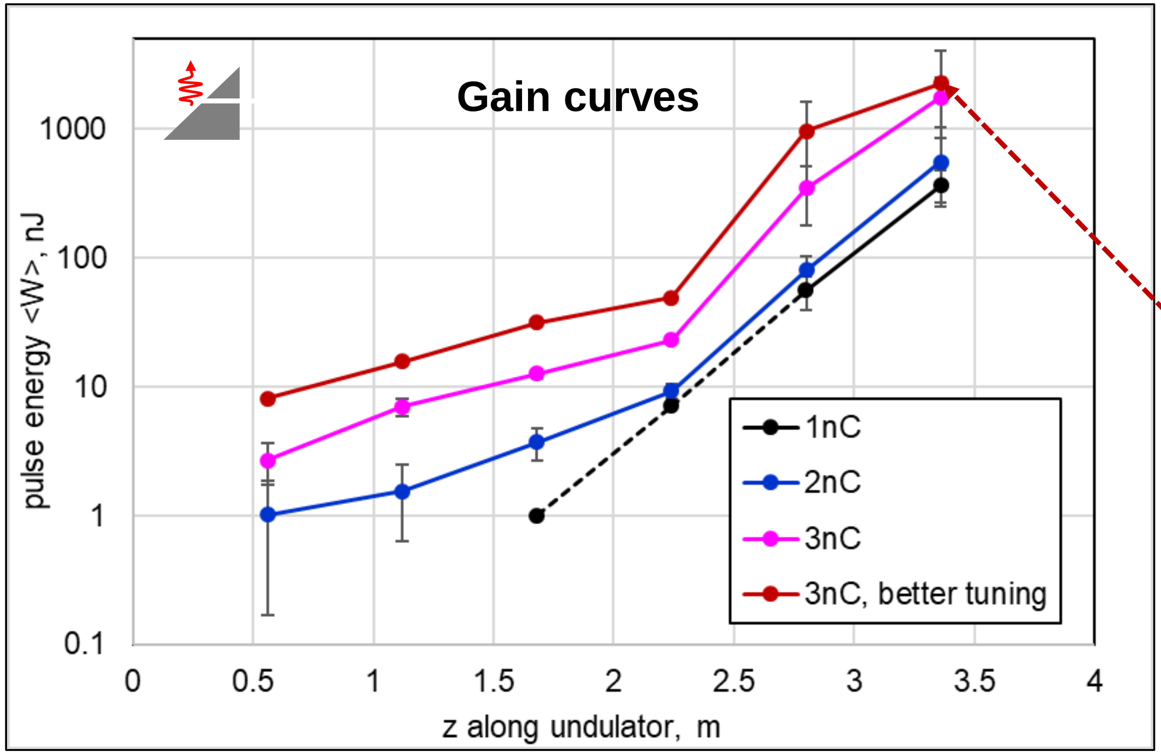
X. Li et al., "Matching of a Space-Charge Dominated Beam into the Undulator of the THz SASE FEL at PITZ", in Proc. 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, pp. 3244-3247.

THz SASE FEL at PITZ: Gain Curves

First Characterization: FEL Gain Curves with HIGH3.Scr2 mirror

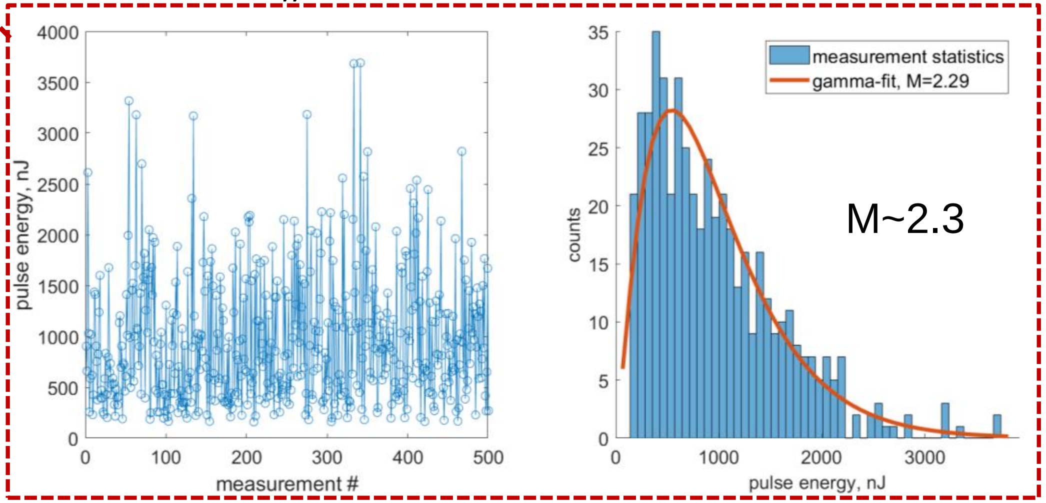
- **Lasing at ~100µm ➔ high gain THz SASE FEL at PITZ!**
- Gain curves at 1, 2 and 3nC





$$\rho(W) \propto \frac{M^M}{\Gamma(M)}\left(\frac{W}{\langle W\rangle}\right)^{M-1}\frac{1}{\langle W\rangle}\exp\left[-M\frac{W}{\langle W\rangle}\right],$$

where $M = \frac{\langle W\rangle^2}{\sigma_W^2}$ is number of modes in the radiation pulse



Band-Pass Filter (BPF3.0) visual inspection repeated

On 16.12.2022

- The " bump ", observed on 04.12.2022, has now decreased (?).
- On the lower surface 3 marks are observed (not investigated before)
- The mark on the upper surface remains

Could be used in the Prach's diagnostics talk?

04.12.2022

THz Studies

High3.Scr3 station: BPF and pyro damaged?

Before installation

04.12.2022A

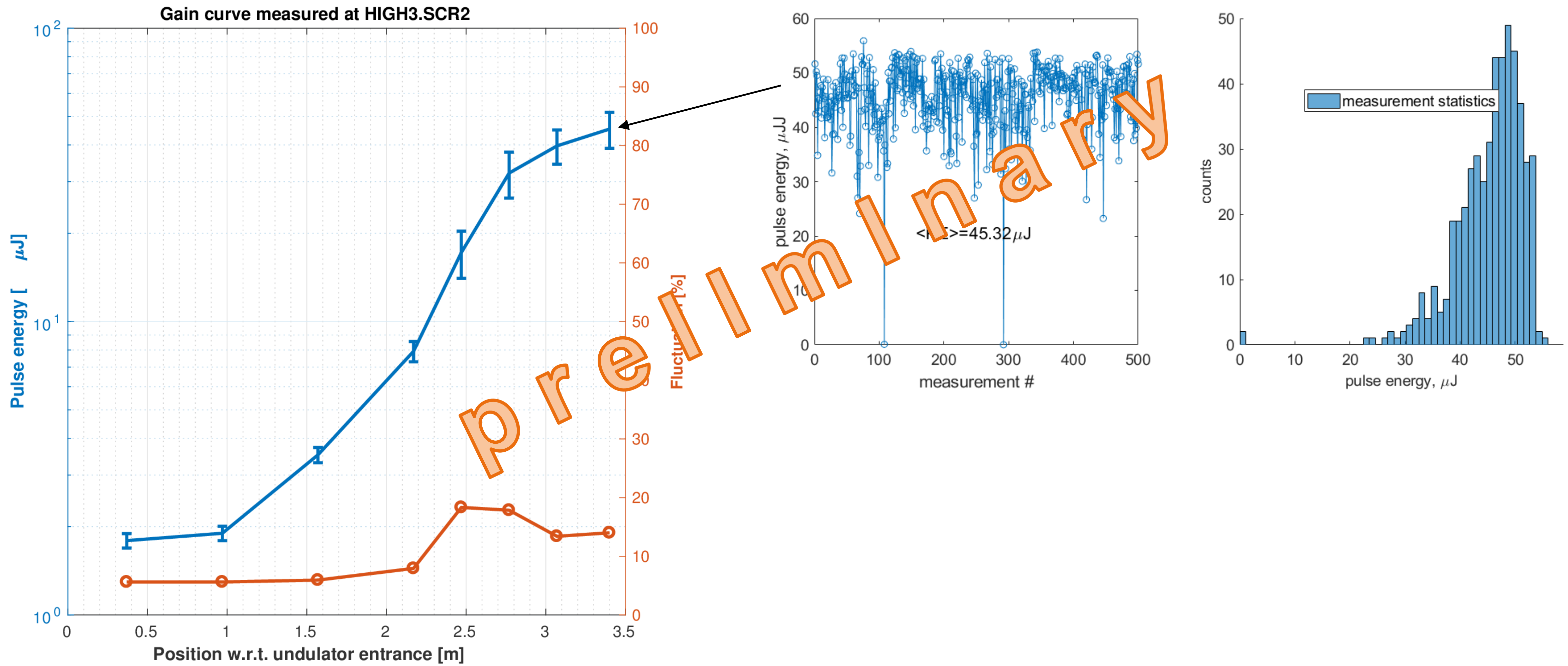
Could be used in the Prach's diagnostics talk?

?Reasons:

- Mechanical stress
- Thermal load
- Radiation load from the TÜV tests
- …

THz Studies

Gain curve of modulated beam 2nC at High3.Scr2 taken on 06.12.2022M ➔ 45µJ!

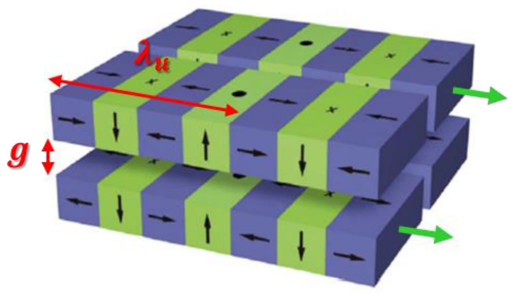


Data saved to /doocs/measure/THz/2022/PulseEnergy/2022/20221206M/GainCurve_0935.mat

THz SASE FEL at PITZ

Undulator and beam parameter space

APPLE- II Undulator*



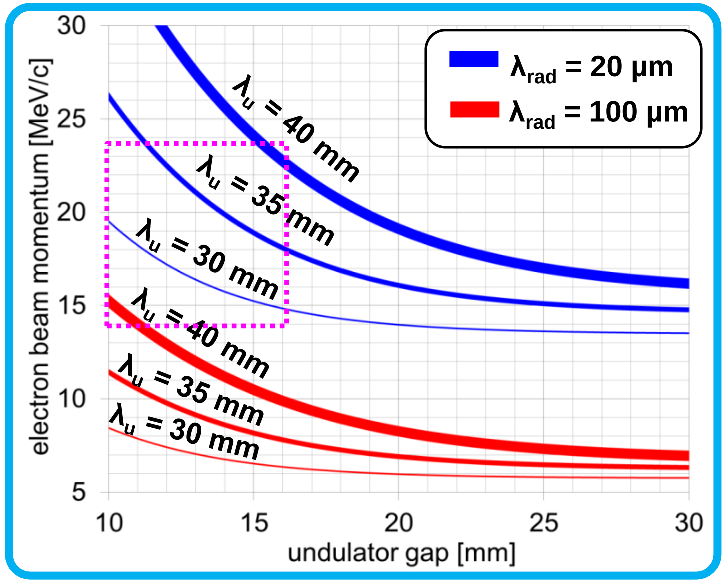
Radiation wavelength

$$\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + K_{rms}^2\right)$$

$$K_{rms} = 0.66 \cdot B_0[T] \cdot \lambda_u[cm]$$

$$B_0 = 1.54e^{\left(-4.46\frac{g}{\lambda_u}+0.43\left(\frac{g}{\lambda_u}\right)^2\right)}$$

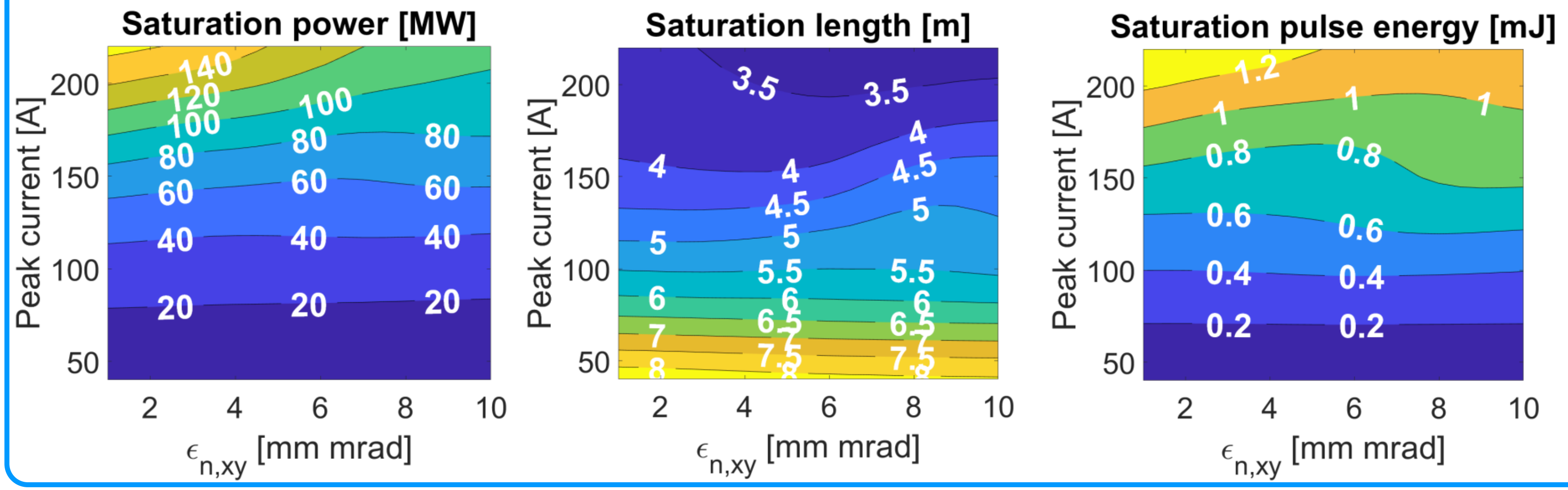
*Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007



Conditions :
λ_{rad} of 20 – 100 µm
Max P_z ~ 22 MeV/c
gap $g \geq$ 10 mm

Selections :
λ_u of 40 mm
22 MeV/c for 20 µm
15 MeV/c for 100 µm

THz SASE FEL Parameter Space with GENESIS (λ = 100 µm)



SASE FEL simulations assuming:

- Helical undulator with λ_u=40 mm
- 4 nC electron beam with 15 MeV/c and ~2 mm rms bunch length

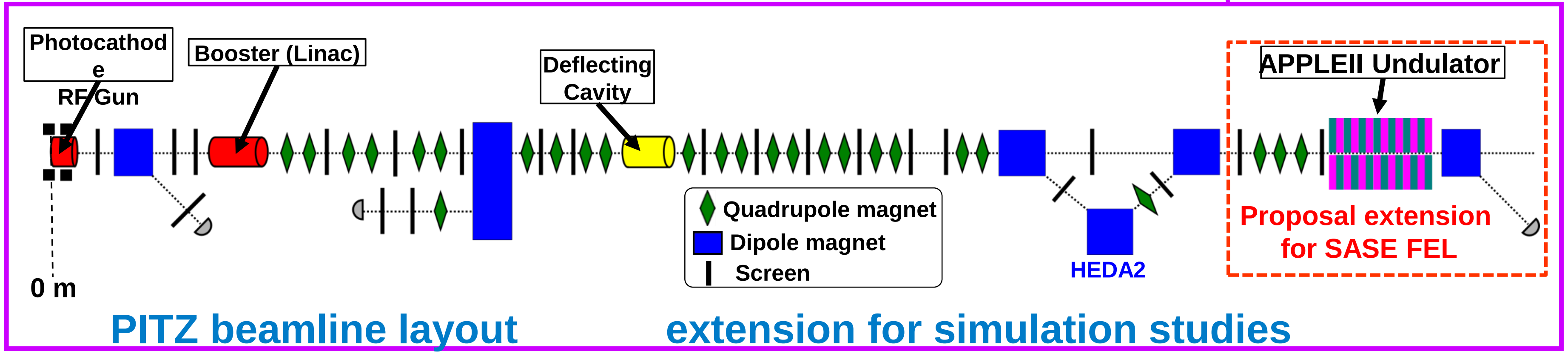
Preliminary conclusions:

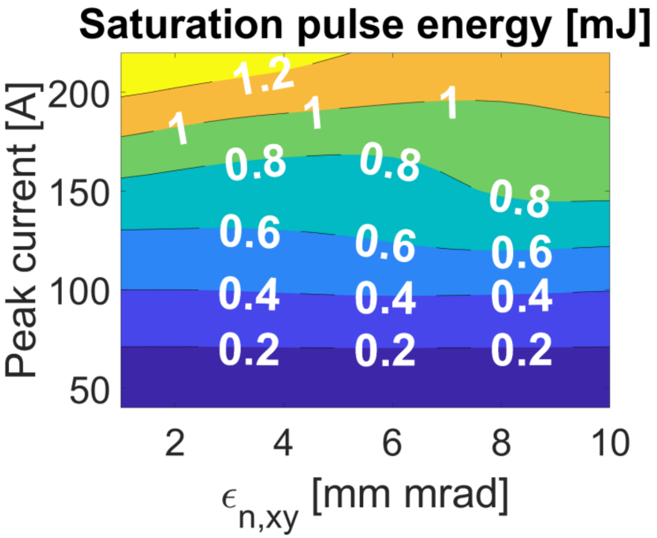
- Beam **peak current** (charge) → most impact
- Transverse normalized emittance ε_n has almost no impact on saturation power

THz@PITZ: original proposals (2018)

PITZ as prototype for an accelerator based tunable THz source for pump-probe experiments at the European XFEL

E.A. Schneidmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen), "Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012





Peak current: 50 to **200 A**
Emittance: 1 to 10 mm mrad

FEL properties from Start-to-End (S2E) simulations

Property	Detail
Central wavelength	106.4 µm
Saturation length	2.94 m
Pulse energy at saturation & U.exit	0.78 mJ & **2.51 mJ**
Peak power at saturation & U.exit	95 MW & 188.7 MW
Radiation pulse duration	18 ps (FWHM)
Spectral width	10 µm (9.4%)

Properties of the APPLE-II undulator used in simulations

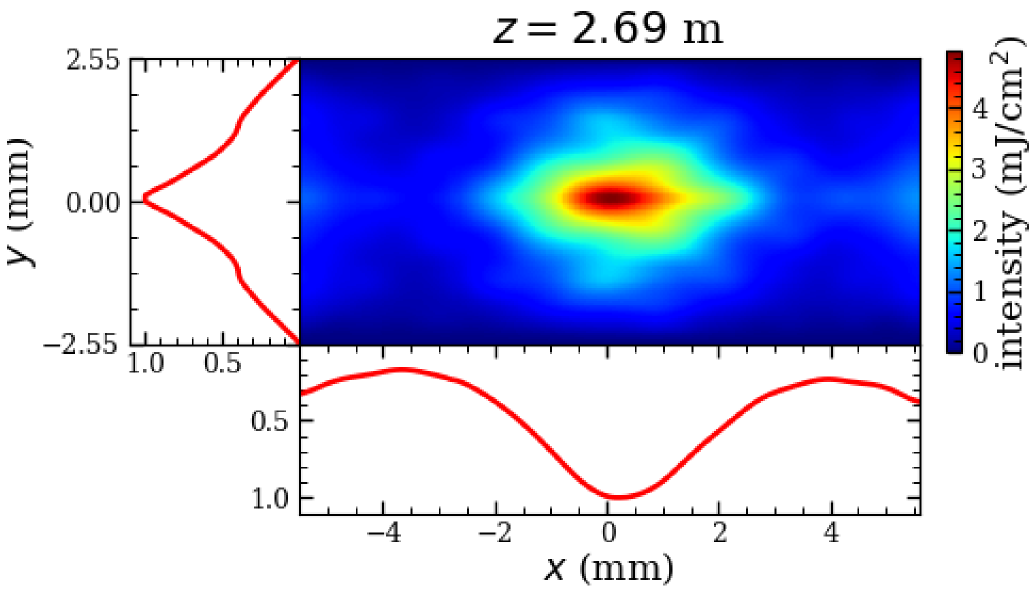
Property	Detail
Undulator type	Helical
K-value	1.82
Period length & total length	40 mm & 7 m (175 periods)

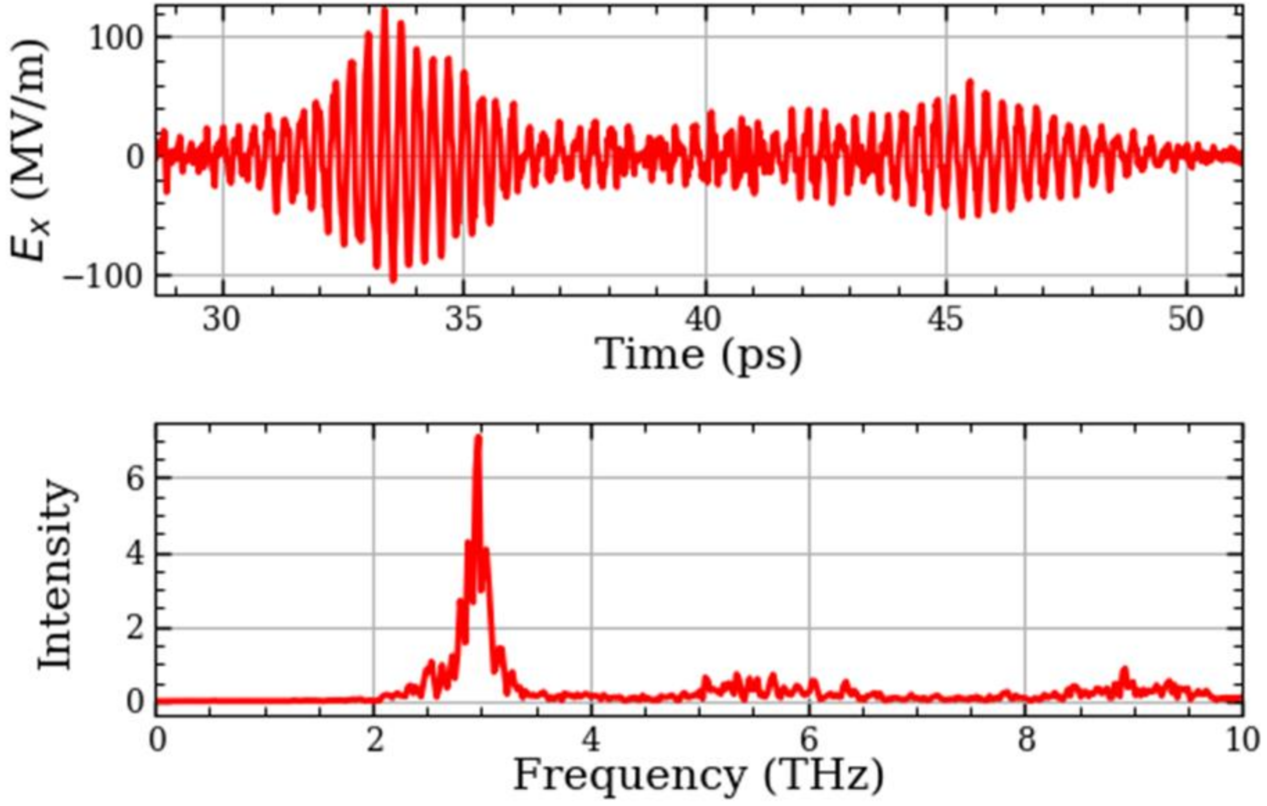
Start-to-end simulation

Proof-of-principle experiment on THz SASE FEL at PITZ

An update would be nice in the talk of Xiangkun?

- Warp: Waveguide effect simulation (100um)



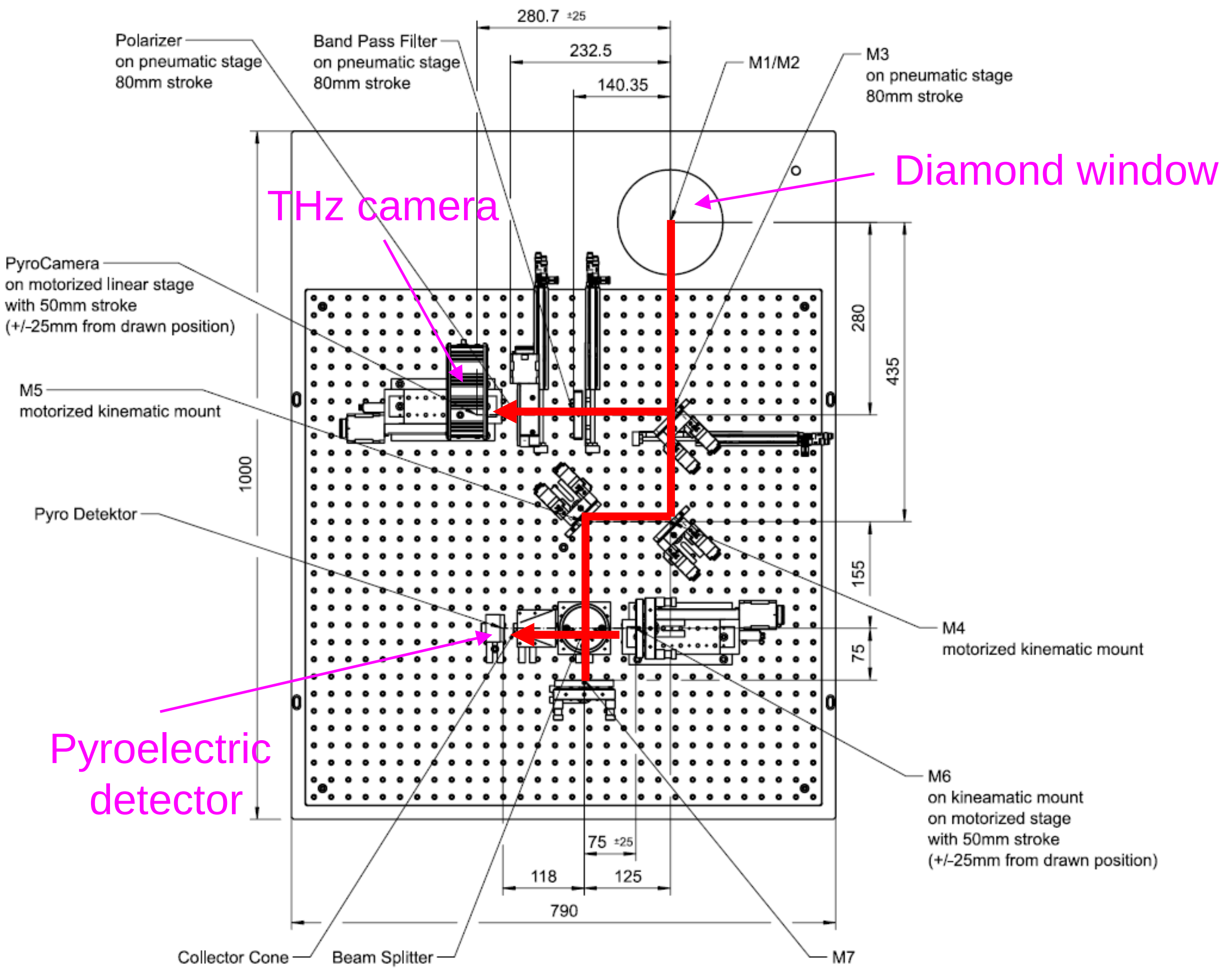


Particle-in-cell code;
Treat vacuum
chamber (11x5 mm)
as conducting
boundaries

Courtesy: X.-K. Li

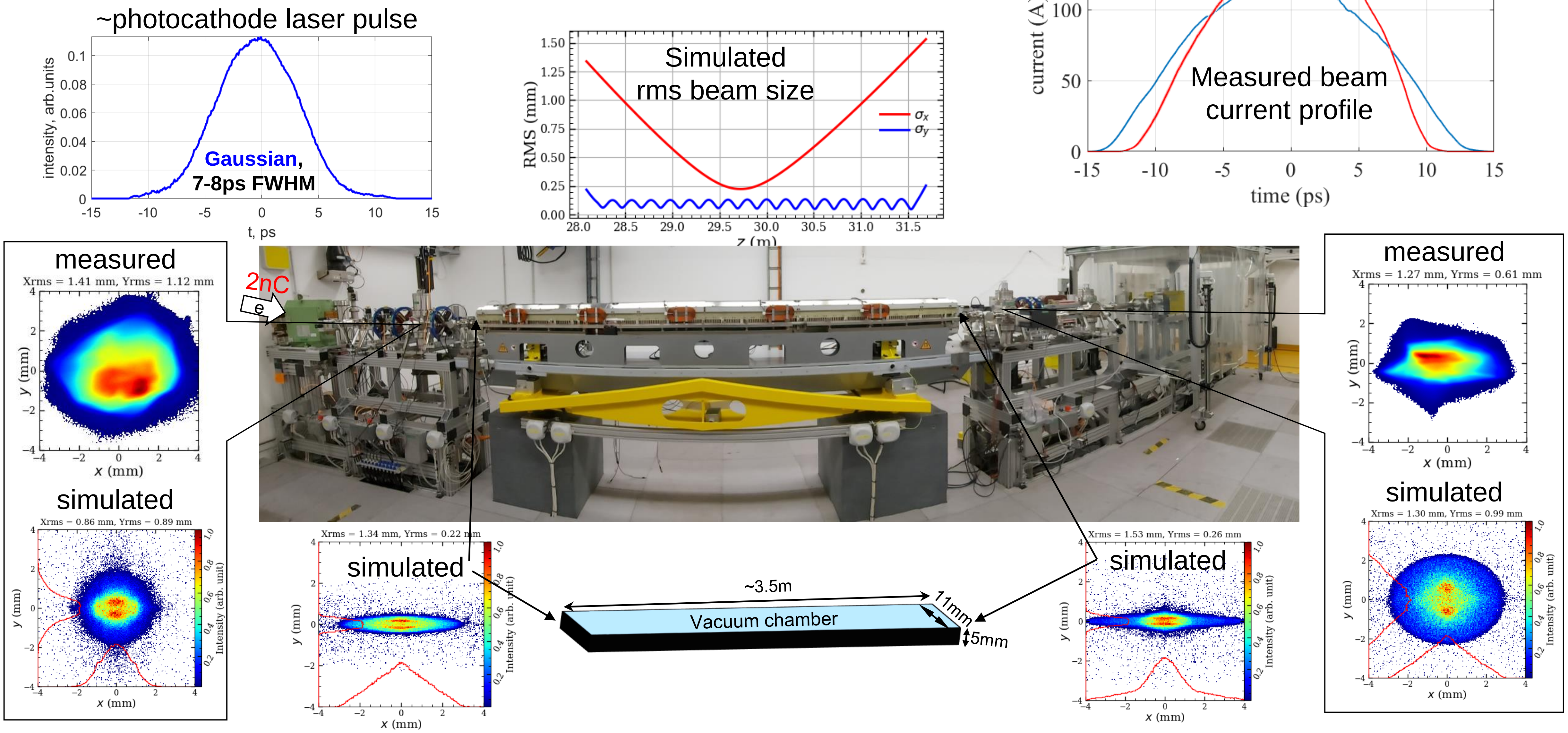
Upgrade of the THz Diagnostic Station at HIGH3.SCR3

- Expected to be ready by spring 2023
- Enclosed system, A pure air circulator unit is used for air purification and humidity reduction.
- THz diagnostics
  - Pulse energy using pyroelectric detectors
  - Transverse profile using a THz camera
  - Polarization using a THz polarizer
  - THz spectrum using a Michelson interferometer
- Diamond vacuum window
- ~1.8 m transport in vacuum, 1-1.5 m transport in air
- Focusing by using 90° off-axis ellipsoidal and parabolic mirrors
- 3 pneumatic actuators, 3 motorized mirror adjusters, 2 motorized linear stages



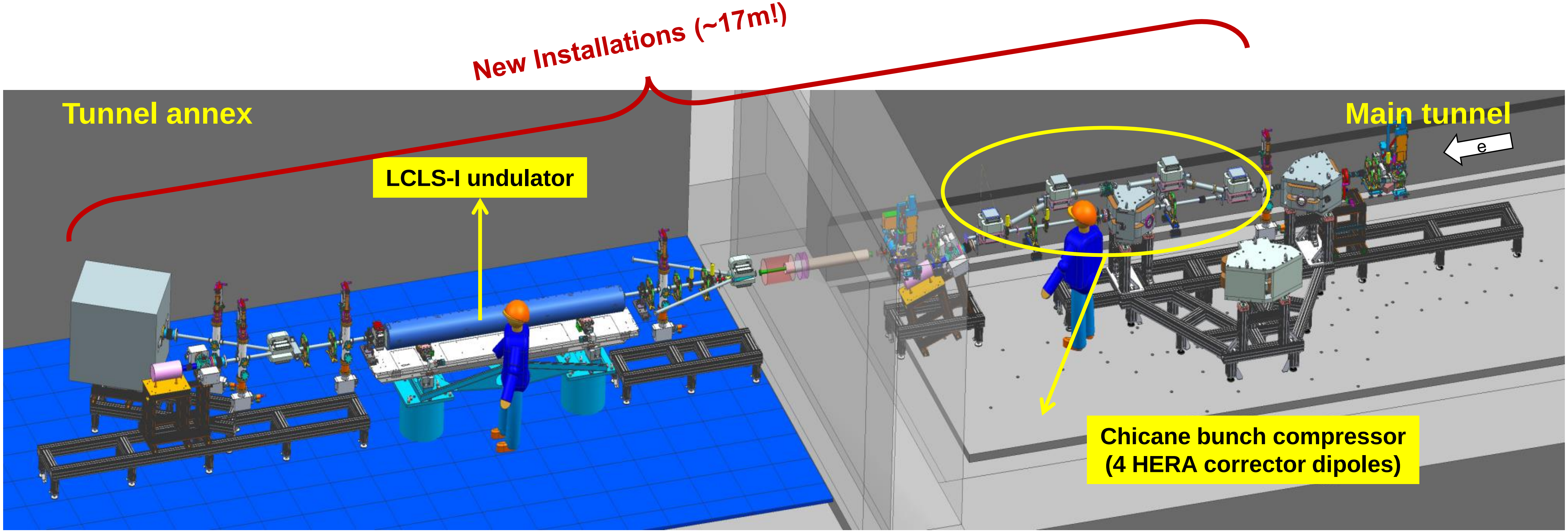
THz SASE FEL at PITZ

Electron beam matching (2nC) for lasing



THz SASE FEL at PITZ: Realization

PITZ upgrade for the proof-of-principle experiment



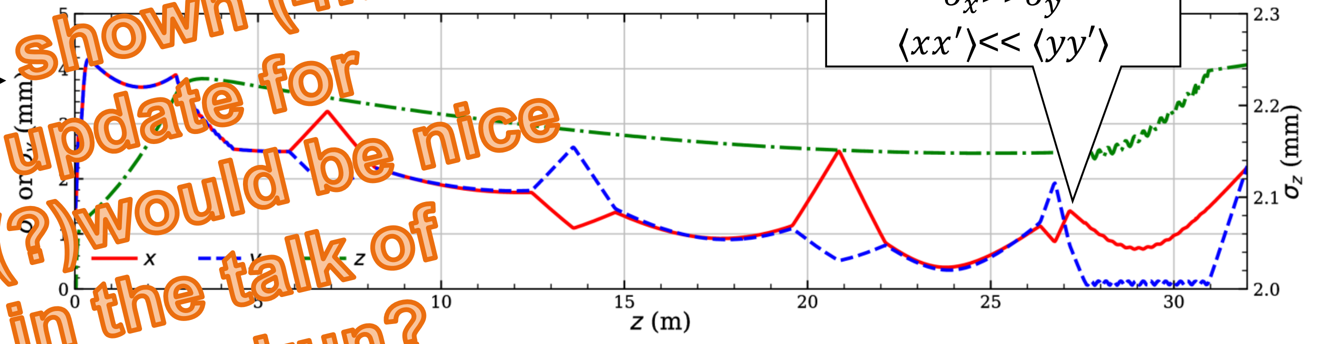
Start-to-end simulation

Proof-of-principle experiment on THz SASE FEL at PITZ (best performance)

To be shown (4nC) + update for 2nC(?)would be nice in the talk of Xiangkun?

- Astra: Photocathode to Undulator entrance
- Genesis 1.3: FEL simulation (input from Astra)

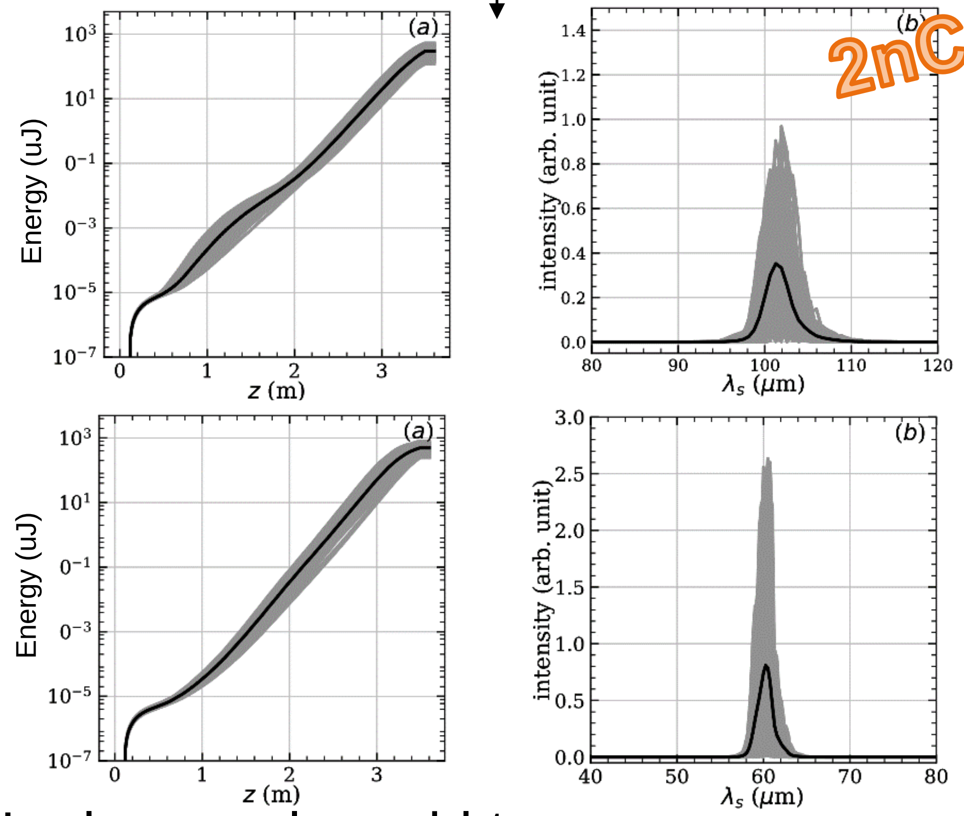
Challenge:
beam **matching** into the undulator
$\sigma_x >> \sigma_y$
$\langle xx' \rangle << \langle yy' \rangle$



Summary of Genesis 1.3 simulation

~100 um

~60 um



THz pulse energy along undulator

Spectrum

Case	100 um	60um	Unit
Momentum	17	22	MeV/c
Pulse energy	**493.1±109.8**	**294.8±83.8**	μJ
Arrival time jitter	1.5	1.1	ps
Center wavelength	**101.8±0.7**	**60.3±0.3**	μm
Spectrum width	2.0±0.4	1.0±0.2	μm

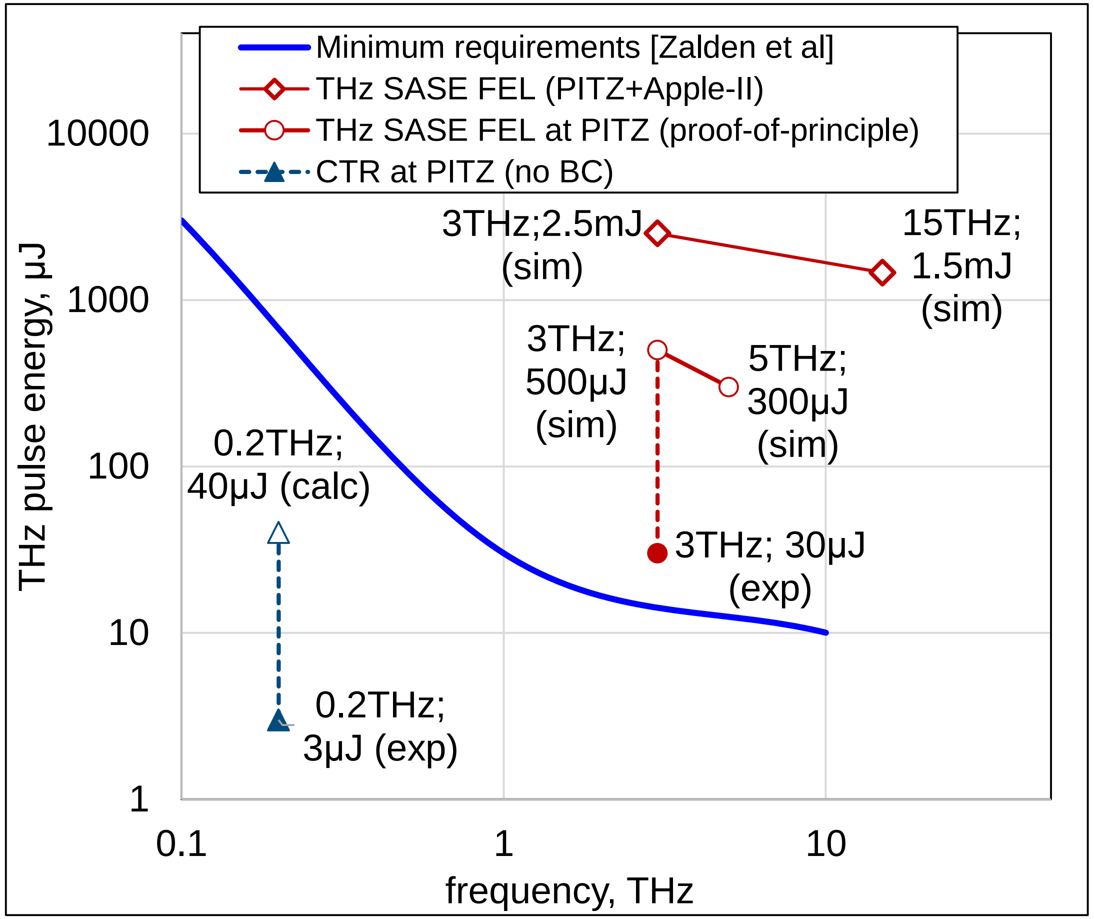
- **Flattop (~20ps)** photocathode laser pulse
- Bunch charge **4nC**

Courtesy: X.-K. Li

NB:
- Genesis simulations in free space, no vacuum chamber (waveguide effect neglected)

Proof-of-principle Experiment on THz Source at PITZ

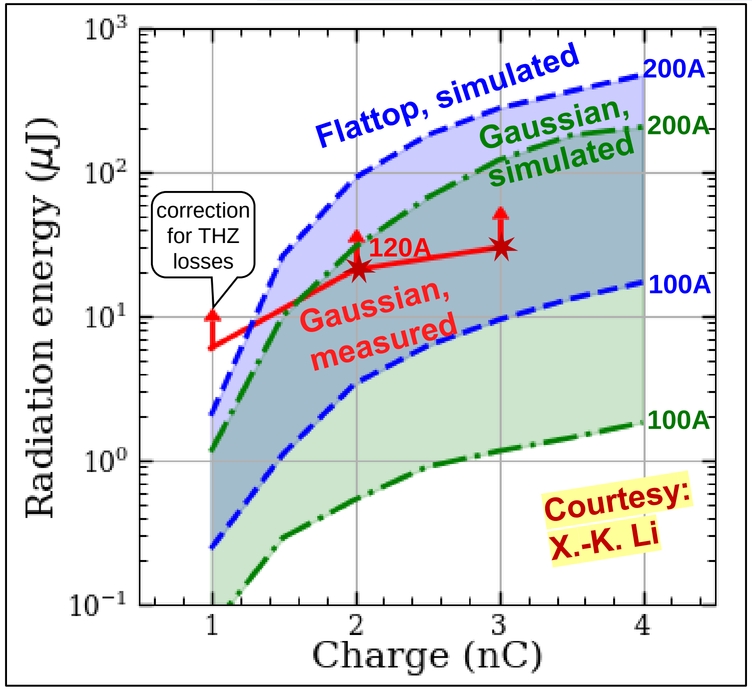
Where we are now and the way to go



parameter	Min. requirements [1]	PITZ (exp)
Bandwidth	1…0.05	~0.02
f [THz]	0.1…**3…20**…30	**3…5**
Pulse energy	3mJ@0.1THz; 30µJ@1THz; 10µJ@10THz	**30µJ@3THz**
CEP	yes	no*
Rep.Rate (burst)	0.1MHz…4.5MHz	1MHz*
Synchronization	<0.1/f	challenge
Polarization	optional	yes

Gaussian photocathode laser, **2-3 nC** bunch charge

Scientific requirements:
[1] P. Zalden, et al., "Terahertz Science at European XFEL", XFEL.EU TN-2018-001-01.0
"..3 to 20 THz is the most difficult to cover by existing sources; at the same time, many vibrational resonances and relaxations in condensed matter occur at these frequencies."



The current project (Proof-of-principle)
→ till end 2023:
- Additional 4 weeks of operation (Σ=11)
- Currently – the only **Gaussian** PC laser pulses
- Milestone: **100µJ**
- NEPAL-P (~mid. 2023)
  → **Flattop** PC laser pulses
- Milestone: **200µJ**+
- 5THz (tunability demonstration)
- Seeding studies
- Detailed characterization of THz
- "Ideal" machine design (CDR)

Conclusions

THz SASE FEL at PITZ

- Photo Injector Test facility at DESY in Zeuthen:
  - develops high brightness electron beams sources and their applications
  - prototype of accelerator based THz source for pump-probe experiments at the European XFEL
- Proof-of-principle experiment ongoing @PITZ (supported by EXFEL):

→ LCLS-I undulator

→ first electrons through the undulator → 22.07.2022

→ 1st THz SASE FEL Lasing → 09.08.2022

→ High gain measured !

→ Strong dependence on beam current and transport /matching

→ Saturation at **>20µJ** with 2nC

→ First seeding experiments **>30µJ** with 2nC modulated beams

High-gain THz SASE FEL at a PITZ-like accelerator **→ it works!!!**

- **Next steps:**
  - Detailed tuning of high-charge beam transport/matching (trajectory model)
  - Setup full THz and e-beam diagnostics (spectral information, THz camera, Disp4)
  - Other dedicated studies (BC, seeded THz FEL, SUR)

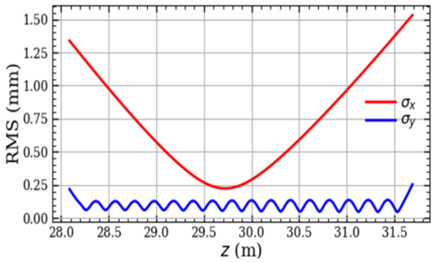
Reference: Saldin E.L., Schneidmiller E.A., Yurkov M.V. “The physics of free electron lasers” - Berlin et al.: Springer, 2000.

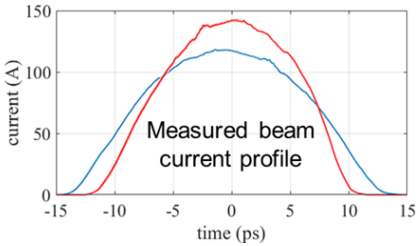
Reference case: 2nC

Cross-check with linear theory of FEL amplifier with diffraction effects

e-beam

parameter	value
Energy, E_0	16.6MeV
γ	32.6
$<\sigma_x>$	0.75mm
$<\sigma_y>$	0.2mm
$<\sigma_r>$	0.55mm
charge	2nC
I_{peak}	125A
$\varepsilon_{n,x,y}$	6 mm mrad
σ_E	~70keV





FEL radiation

parameter	value
λ_{rad}	100µm
Q	0.429
A_{JJ}	0.745
θ_l	0.107
γ_l	12.2
Γ	$(0.23\mathrm{m})^{-1}$

$$\lambda_{rad} = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$Q = \frac{K^2}{4+2K^2}$$

$$A_{JJ} = J_o(Q) - J_1(Q)$$

$$\theta_l = K/\gamma$$

$$\frac{1}{\gamma_l^2} = \frac{1}{\gamma^2} + \frac{\theta_l^2}{2}$$

$$\Gamma = \sqrt{\frac{I_{peak}A_{JJ}^2\omega^2\theta_l^2}{2I_A c^2\gamma_l^2\gamma}}$$

FEL dimensionless

Parameter	Value
Diffraction B	0.164
SC $\hat{\Lambda}_p^2$	0.532
FEL ρ	0.0104
EnSpread $\hat{\Lambda}_T^2$	0.165
Waveguide $\Omega*$	4.9

$$B = \frac{2\Gamma\sigma_r^2\omega}{c}$$

$$\hat{\Lambda}_p^2 = \frac{4c^2}{[\theta_l\sigma_r\omega A_{JJ}]^2}$$

$$\rho = \frac{\gamma_l^2\Gamma}{\omega/c}$$

$$\hat{\Lambda}_T^2 = \frac{\sigma_E^2}{[E_o\rho]^2}$$

$$\Omega = \Gamma R_{eff}^2\omega/c$$

undulator system

parameter	value
λ_u	30mm
K	3.47
Vacuum chamber R_{eff}	4.2mm

$$E_x(z) \propto \exp(\Lambda \cdot z)$$

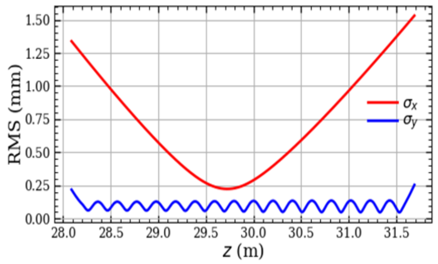
Reference case: 2nC

Cross-check with linear theory of FEL amplifier with diffraction effects

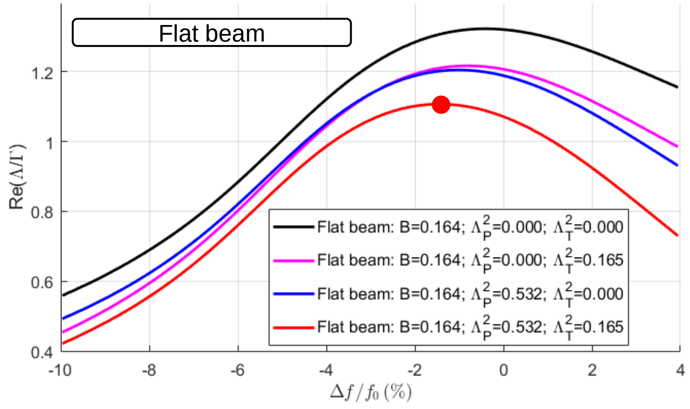
The gain parameter of the FEL amplifier

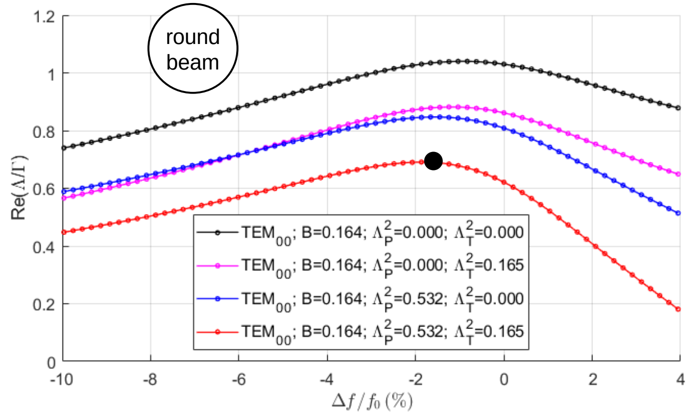
$$\Gamma = \sqrt{\frac{I_{peak} A_{JJ}^2 \omega^2 \theta_l^2}{2 I_A c^2 \gamma_l^2 \gamma}} = (0.23m)^{-1}$$

Parameter	Value
Diffraction B	0.164
SC $\hat{\Lambda}_p^2$	0.532
FEL ρ	0.0104
EnSpread $\hat{\Lambda}_T^2$	0.165
Waveguide $\Omega*$	4.9



Eigenvalue problem
→ beam radiation modes
$E_x(z) \propto \exp(\Lambda \cdot z)$,
Λ → field gain ($\mathrm{Re}\Lambda$)





SASE 2nC: Linear theory versus measurements